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# THESIS

**SOFTWARE ARCHITECTURE FOR ANTI-SUBMARINE WARFARE UNMANNED SURFACE VEHICLES**

by

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The U.S. Navy seeks to reduce costs associated with anti-submarine warfare (ASW) operations by exploring the use of unmanned surface vehicles (USVs). Currently, the process of finding submarines tends to be tedious and manpower intensive due to the high volume of acoustic data with limited means to filter for valuable information. Therefore, innovative software frameworks are required to transition from a "one-to-many" to a "many-to-one" USV/ human interaction model. By examining potential software frameworks, this thesis addresses many of the benefits and challenges inherent to using USVs in dynamic maritime environments. Furthermore, this evaluation provides a building block for the continued development of USV software systems.

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**SOFTWARE ARCHITECTURE FOR ANTI-SUBMARINE WARFARE UNMANNED SURFACE VEHICLES**


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Submitted in partial fulfillment of the requirements for the degree of

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# ABSTRACT

The U.S. Navy seeks to reduce costs associated with anti-submarine warfare (ASW) operations by exploring the use of unmanned surface vehicles (USVs). Currently, the process of finding submarines tends to be tedious and manpower intensive due to the high volume of acoustic data with limited means to filter for valuable information. Therefore, innovative software frameworks are required to transition from a "one-to-many" to a "many-to-one" USV/human interaction model. By examining potential software frameworks, this thesis addresses many of the benefits and challenges inherent to using USVs in dynamic maritime environments. Furthermore, this evaluation provides a building block for the continued development of USV software systems.

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# LIST OF ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| AI | artificial intelligence |
| ASW | anti-submarine warfare |
| BB | bottom bounce |
| BG | battle group |
| CIEA | Classification, Identification, and Engagement Area |
| C/COI | critical/contact of interest |
| COLREGS | IMO's International Regulations for Preventing Collisions at Sea |
| CSG | carrier strike group |
| CVW | carrier air wing |
| CZ | convergence zone |
| DICASS | directional command activated sonobuoy system |
| DIFAR | directional frequency analysis and recording |
| DP | direct path |
| EO | electro-optical |
| ESM | electronic support measures |
| FLIR | forward looking infrared |
| HSM | helicopter maritime strike squadron |
| HVU/T | high value unit/target |
| I/O | input/output |
| IFF | interrogate friend or foe |
| IMO | International Maritime Organization |
| ISR | intelligence, surveillance, and reconnaissance |
| LCS | Littoral Combat Ship |
| MAD | magnetic anomaly detector |
| MODLOC | miscellaneous operating details, local operations |
| MPRA | maritime patrol and reconnaissance aircraft |
| NVG | night vision goggles |
| RADAR | radio detection and ranging (depreciated) |
| ROE | rules of engagement |
| SA | surveillance area |

| | |
|---|---|
| SAG | surface action group |
| SONAR | sound navigation and ranging (depreciated) |
| SSP/SVP | sound speed profile or sound velocity profile |
| SURTASS | surveillance towed array sensor system |
| TTP | tactics, techniques, and procedures |
| UMS | unmanned system |
| USV | unmanned surface vehicle |
| UxV | unmanned unknown/undefined vehicle |
| VA | vital area |
| WSM | water space management |

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# I. INTRODUCTION

## A. OVERVIEW / MOTIVATION

Autonomous systems appear to be in vogue, both in commercial and defense sectors. News headlines capture the accomplishments and challenges faced by autonomous systems every day. In this environment, the U.S. Navy seeks to better understand this domain and how it can be apply knowledge gained to the problem of making Anti-Submarine Warfare (ASW) less "dull, dirty, and/or dangerous" to human operators.

Eliminating the adversary from the equation for a moment, it should be stated that the maritime environment is a challenging domain for anyone who hopes to operate in it. From time immemorial, mariners have been battling the effects of salt, water, wind, and sun on machines, and the effects of distance and motion on people. No matter the century, or the technology, these factors are constantly at work—to the detriment of the mariner. It is then the challenge for an architect or designer to try to mitigate these forces, and to ease the life of the people who put to sea. The notion applies equally as well to the would-be engineer who is designing a system, hardware or software, to operate in this domain. Then, to make the task even more challenging, add in the assumption that someone else is trying to sink your design or halt your mission.

There is little published material on autonomous vehicle systems that operate on the water's surface in support of finding submarines hidden beneath. Additionally, there is a lack of open discussion about software systems that could be used to control these systems to make the jobs of the human operators easier.

## B. RESEARCH QUESTIONS

This thesis sets out to answer the following questions:

- What kinds of interactions will USVs need to have with other platforms in Maritime Shield and Protect Passage ASW and what degree of human operator control will they need?

- Which aspects of these missions could the USVs carry out autonomously and what kind of autonomous decisions will be needed to carry out the missions more effectively than with current manned platforms?
- How does one determine the value added by autonomy and decide which aspects of the USV mission would benefit most from automation?

### C. LITERATURE REVIEW

The first job of any software architect is to understand the requirements of the stakeholders. Sometimes these requirements are explicitly stated, but most of the time, they are implied. However, being able to distill a customer's requirements into a list of bullets is not sufficient and is only the initial step. The next step is to actually begin the design phase where the developer will attempt to craft solutions that meet the needs of the customer. To aid in this process, the developer should become familiar with the domain(s) that their solution is being designed for; in the case of this study, the domain is ASW with USVs, which includes the maritime environment. To this end, it is instructive to begin with a brief review of the literature that shaped the trajectory and understating of the research domain.

In 2007, the U.S. Navy published its vision for future unmanned systems in [1], which outlined the potential use of USVs in support of the ASW mission. In 2013, the RAND Corporation took the idea further and suggested in [2] specific sub-categories of ASW missions that a USV might perform well in. These two publications serve as the launch pad for this research study.

To better understand the role of artificial intelligence in designing autonomous systems, S. Russell and P. Norvig jointly authored a textbook [3] that covers many of the fundamentals of modern AI. Additionally, the anthology of essays titled *Human-Robot Interactions in Future Military Operations* and edited by M. Barnes and F. Jentsch contains a number of essays that discuss human-robot interactions. The biggest takeaway is in [4], which states a theoretically ideal mix of humans to robots for remote operations. The term "robot" and "autonomous system" are often used synonymously, and for most applications, the differences in terms are negligible. Many lessons that the field of robotics has learned can easily be applied to the broader field of autonomous systems.

Furthermore, the book by B. Mishra titled *Autonomous System: A Beginners Guide to Design their Own Autonomous System from a Scratch* discusses how to build an autonomous system/robot from the ground up, the discussion on artificial neural nets (ANN) influencing this project's design. The anthology titled *Autonomous Vehicles: Intelligent Transport Systems and Smart Technologies* addresses many topics on the challenges of designing a hardware/software interface supporting autonomy.

From a more philosophical perspective, the paper by A. Bouchard and R. Tatum titled "Verification of Autonomous Systems: Challenges of the Present and Areas for Exploration" discusses a shift in the way of thinking about autonomous systems. Specifically, they echo many industry leaders that say that Levels of Autonomy, as a concept, is dead. They propose instead to see autonomous vehicles as a set of skills and abilities. These two concepts form a lens in which to view the various functions of an unmanned system (UMS).

In his 2007 master's thesis [5], A. Oliveira outlines the software architecture for an oceanographic research USV. The paper may be a little technical for a wider audience, but many of the ideas he discusses are applicable to any future USVs. In his thesis, he outlines the benefits to using a Linux based operating system (OS) over other operating systems like Windows. Also, he recommends avoiding the use of threaded or multi-threaded programs and instead recommends using single-thread/single process programs. His reasoning is clearly outlined and served as an influence to my design.

Finally, Professor. Berzins's class at NPS as well as the book [6] he co-wrote with Professor Luqi proved invaluable to understanding the software architecture required by autonomous systems. This was further augmented with R. Hanmar's *Pattern-Oriented Software Architecture for Dummies,* which discusses different approaches to designing software, as well as E. Evans's *Domain-Driven Design*: *Tackling Complexity in the Heart of Software,* which talks about designing software in the context of a specific knowledge domain like ASW. Both works proved to be valuable tools in channeling my vision for the ASW USV's software.

## D. THESIS ORGANIZATION

The remainder of this document is organized in the following manner:

Chapter II is a primer on anti-submarine warfare distilled from the U.S. Navy's foremost-unclassified publication on acoustics known as the RP-33, with appropriate context informed by my experience as a qualified aircraft and mission commander in the Sikorsky SH-60B "Bravo" Seahawk multi-mission helicopter. In order to develop and employ a useful USV, it is important to understand the environment it will operate in, other systems that it will support and complement, and the threats it will attempt to detect or defeat.

Chapter III focuses on introducing the reader to concepts in automation and artificial intelligence (AI). The mere mention of AI conjures up ideas of cyborgs attempting world domination; however, AI is really nothing more than very cleaver programs that mimic certain human behaviors. AI is important when considering USVs and ASW because it is difficult to "brute-force" detection of submarines and predict their actions. Well thought out AI agents can help reduce the complexity of a situation and can help focus a human on tasks that are more difficult for a computer to handle.

Chapter IV lays out a framework for the software architecture for an ASW USV. This chapter discusses challenges, assumptions, and benefits to developing a software system to handle multiple USVs.

Chapter V discusses critical though peripheral issues to the USV software development. Finally, Chapter VI brings it together with concluding thoughts and recommendations for future work.

# II. BACKGROUND

Anti-Submarine Warfare is best thought of as both an art and a science. It is a science because it is organized, systematic, based on proven research and theories, and, for the most part, is largely repeatable. In order to further support this point, consider the amount of knowledge, equipment, and training that is required to successfully conduct operations in this environment. It is an art because even with dedicated study of all the tactics, techniques, and procedures (TTPs) it is still a game of chance impacted by many factors, with the enemy playing a significant role. In warfare it is said that the enemy “gets a vote,” an observation of the reality that not all factors are knowable, and so one must therefore be prepared for the unexpected. To inform later chapters, the following sections attempt to set a baseline of understanding.

## A. THE SUBMARINE—A (VERY) BRIEF HISTORY

The modern military submarine can trace its roots back to 1776 and David Bushnell’s *Turtle*. It was intended to approach a ship unobserved, drill a hole in the bottom of the hull, leave an explosive charge, and then evacuate before detonation. Due to some critical design flaws, the plan failed, but the concept persisted as noted in [7]. The submarine gained prominence and notoriety during both of the previous World Wars where the Germans used it to great affect at slowing, but not stopping, the stream of men and material from the United States to its allies. Today, the submarine retains its historic mission of striking commercial shipping and military targets, as well as performing long range strike warfare and special operations.

### 1. Purpose

The main purpose of a Navy is power projection—both military and economic, with its chief effort to ensure that the Sea-Lines-of-Communication (SLOC) remain open for commerce and military movement. It is best to think of a SLOC as an imaginary line that departs one country and traces a route to another location, along which people, goods, services, and ideas may transit. To cut these routes, or to make them prohibitively expensive, can have devastating consequences to those on both ends of the SLOC.

A submarine's primary purpose is to disrupt the SLOCs by threating or destroying shipping. When trade is disrupted, it can have severe consequences—locally, regionally, and globally. For a more detailed history on submarines, consult [7].

### 2. Operation

A submarine is a stealth asset, capable of disappearing beneath the waves to strike out at surface or sub-surface ships, launch long range missile strikes, conduct infiltration operations, or to conduct espionage. Unlike surface ships, a sub cannot be easily monitored or tracked, and so its intentions are usually unknown. This is what makes a sub such a good deterrent—its ability to strike first without notice. Additionally, this particular advantage is a major risk for an opponent and will usually result in the submarine being a higher priority target for prosecution and neutralization.

According to Part II, Section 3, Article 20 of the United Nations Convention on the Law of the Sea (UNCLOS), a submarine that is transiting innocently MUST do so on the surface while showing their flag while in "Territorial Waters" [8]. This should be interpreted as such: in failing to comply with these requirements, a submarine is purposefully being evasive and is likely conducting operations that the coastal nation would find aggressive or even hostile. This thought can be applied to the open ocean, or "International Waters/High Seas," to include the contiguous zones as well. If a submarine wants to be "friendly" it will do so on the surface as this nullifies his advantages and shows that he is not as much of a threat. Conversely, if a submarine is detected, and does not surface to show good will, then it can be assumed that the submarine may have ulterior motives, and needs to be treated with suspicion. Consider this analogy: while it may be against the laws of some jurisdictions to wear masks or disguises, it is not fully prohibited. However, when asked to remove said articles by a member of law enforcement, and then an individual refuses to comply, and then their motives are immediately questioned. Was their intent to be disguised in the commission of a crime, or are they suspected of crimes and were trying to conceal their identity to avoid arrest?

This is a fundamental concept in ASW: if a submarine is trying to de-escalate tensions, then they would do so on the surface, or would otherwise establish communications. Failure to do so implies that they do not want to be found. This is why searching for submarines is referred to as "hunting" and why there exists processes called "kill chains" because like the criminal referred to above, the situation could turn aggressive quickly, and friendly forces might be required to use deadly force to subdue the would be assailant.

## B. THE UNDERWATER ACOUSTIC ENVIRONMENT

The underwater acoustic environment is not a simple system, and entire books have been written trying to capture the precise nature of this dynamic domain. The following sections only include the very basics, and the dedicated scholar is encouraged to seek further information with a recommended starting point being the Naval Oceanographic Office's (NAVOCEANO) Reference Publication 33, commonly referred to in the ASW business as "The RP-33."

### 1. Sound Waves

The RP-33 states, "Sound originates as a wave motion produced by a vibrating source" that requires a medium like air or water for transmission. Sound waves have the same properties as other waveforms (e.g., electromagnetic waves) such as frequency, wavelength, amplitude, and speed. Sound will typically emit omnidirectionally from a sound source, but it can be hard to visualize this phenomenon; therefore, it is easier to think of sound as being a ray (like a light ray) being emitted from a source. If the medium was uniform, then the sound ray would travel a straight path until it was reflected off some surface. However, the ocean is far from uniform, and so sound has a tendency to travel in curved paths [9].

### 2. Speed of Sound

The speed of sound in water is approximately 1500 m/sec, with changes in speed being a function of water temperature, salinity, and pressure. These factors are highly variable depending on geographic location, season, time of day and depth [9].

### 3. Sound Speed Profile (SSP)

The sound speed profile is a graphic representation of the speed of sound in respect to temperature, depth (pressure), and to a lesser extent, salinity. See Figure 1. At shallow depths (< 1500m), temperature plays the most significant role in affecting the SSP. However, at approximately 1500m, temperature decreases slowly or becomes isothermal for increasing depth, and yields to pressure for dominance in affecting the SSP. Generally speaking, when the rate of temperature change is greater than the rate of pressure change, then temperature will be the dominant factor on the SSP. Specifically, as temperature decreases so too does the speed of sound. Conversely, when the rate of pressure change is greater than the rate of temperature change, pressure will be the dominant factor in calculating the SSP. Specifically, once the rate of temperature decrease slows or halts, pressure becomes dominant and the speed of sound will increase. A property known as depth excess, useful in predicting convergence zones (covered later), will occur when the speed of sound increases back to where it initially began to decrease. Salinity, for the most part, plays a minimal role in deep open-ocean environments. This is because most of the world's oceans tend to be close (+/- 2 ppt) to the global average of 35 parts per thousand (ppt) of salt, so planners figure salinity to be relatively static. This assumption is not valid in shallow water or polar environments where the influx of fresh water may play a significant role on regional salinity [9].

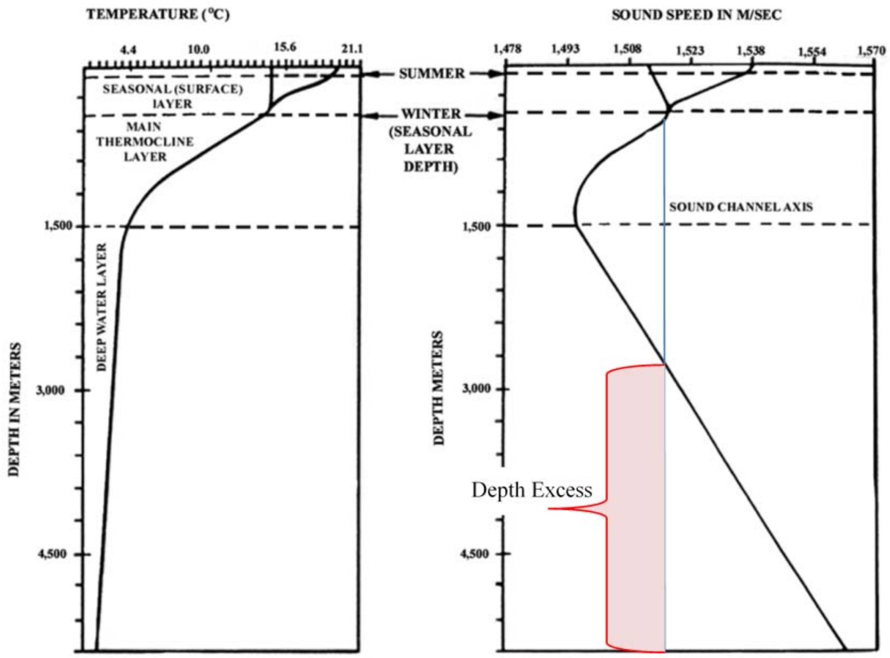


Figure 1. Sound Speed (Velocity) Profile. Adapted from [9].

#### 4. Sound Propagation

As soon as a sound is created, its behavior is subject to the peculiarities of the medium it is being transmitted through. As previously mentioned, if the ocean were uniform then sound would travel in straight lines, but because it is not uniform, sound travels in seemingly curved paths. This is the result of refraction that is encapsulated in Snell's Law. The RP-33 defines Snell's Law as "a ray going from a region with one speed will have a different direction in a second region which has a different speed." This concept can be applied multiple times over multiple layers or regions of water that hold uniform properties. It should be noted that, except in a vacuum, the refracted ray will bend towards areas of lower sound speed [10]. Therefore, the general observation is that sound generally travels away from areas that have a higher speed of sound, and will travel towards areas that have slower sound speeds leading to the appearance that sound travels in curved paths [9]. The basic mnemonic is higher away, lower towards.

### *a. Propagation Loss*

As sound waves travel through the ocean, the pressure of the sound wave diminishes, this is known as propagation loss. It is important to understand how pressure, energy, and sound intensity interact because it impacts the detection process. The lower the signal level, the harder it is to detect. The seven main factors that impact propagation loss are losses due to: spreading, absorption, scattering, the bottom, the surface, diffraction, and multi-path interference [9].

**Spreading Loss:** There are two main types of spreading loss, spherical and cylindrical. Spherical spreading loss can be thought of as the ideal or theoretical model for spreading loss where sound emits from a source in all directions without any constraints. Cylindrical is closer to reality where you have an upper (surface) and lower (bottom) boundary that contain sound energy. In the spherical model, sound intensity decreases by 6dB per distance from the source doubled. Cylindrical loss is slightly better at only a decrease of 3dB per distance doubled.

**Absorption Loss:** As a sound wave travels from its source, some of the mechanical energy is converted into heat, which causes a loss of sound intensity. Generally speaking, absorption is proportional to the square of the frequency [9]. This means that lower frequencies will travel further, and higher frequencies will be absorbed sooner.

**Scattering Loss:** Because a water column is not uniform and there will be many variations of temperature and salinity even in a fairly uniform layer, some energy will be refracted and reflected away from the main sound wave causing a general loss of intensity [9].

**Bottom and Surface Loss:** These two types of loss are related in that they are the result of the acoustic energy interacting with the edge of the medium (water). In the case of the bottom, it is the composition of the ocean floor, and in the case of the surface loss, it is wave action [9].

**Multi-path Interference:** As rays of sound depart a source in different directions, they may eventually meet with one another. When these rays meet, they may either do so constructively (increase in sound intensity) or destructively (decrease in sound intensity) depending on the difference in the lengths of the two paths [9].

#### *b. Propagation Paths*

The RP-33 recognizes six different types of propagation paths. It is not necessary to cover all of them. The most important of the propagation paths for ASW in and around the battle group is direct path or "DP." DP propagation is sound that has been emitted directly from its source that travels an "approximately straight-line path between sender and receiver" without being subject to signal loss or frequency shift due to interactions with the bottom or surface. If you have DP contact, your vessel of interest is close. It is also worth mentioning convergence zone or "CZ" propagation. When the ocean is deep enough to have a depth excess, and is free of obstructions, sound can travel for a very long distance. To give some perspective, the typical directional frequency analysis and recording (DIFAR) sonobuoy deployed from aircraft has a relatively short detection range of only a few thousand yards with DP contact. However, when CZs are possible due to depth excess, detection ranges may extend 30 Kyds to 60 Kyds (15 to 30 NM). In some regions, it is possible to have multiple CZs, so the true detection range could be extended even further. For example, if your acoustic prediction software estimated CZ contact to be possible out to four CZ, then one might be able to detect a submarine as far as 60 to 120 NM away. Depending on the use, this contact can be more beneficial than direct path as it provides the listener with advanced notice of an approaching submerged vessel [9]. This works both ways though, and a submarine may be able to detect the listener's presence.

### 5. Sources of Noise

In ASW, as with many fields, it is important to separate signals from noise. To recognize when one has a signal, one has to discriminate the noise. The RP-33 classifies two types of noise: ambient and self. Ambient noise is that which is part of the environment independent of the actions and movements of the search platform. Ambient noise includes maritime traffic, melting/forming ice, biologics, and marine mammals. Self-noise covers everything caused or related to the search platform; examples include machinery noise, propeller noise, hydrodynamic noise, and aircraft noise. Self-noise can interfere with the search platform's instruments and give away the platform's position to an enemy [9].

### 6. Deep Water versus Shallow Water

In deep water, sound can travel a great distance before it is fully absorbed, which can allow a careful listener to detect a submarine. However, to fully exploit some of these properties requires sensors that can go deep enough to capture this information. When the depth excess is greater than 200 fathoms (1200 ft.) then there exists a strong (>80%) probability that CZ propagation is possible. Recall from the previous section that CZ propagation can be detected 15–30 NM from the source, and multiple CZs may exist [9]. A noisy submarine in deep water is a submarine that wants to be found. Between shallow and deep water, deep water is considered the easier environment. Shallow water is much more sensitive to the effects of weather, geography/topology, and changing temperatures and salinity. Additionally, to complicate matters, shallow water also contains the highest density of maritime traffic, which means that there is a lot of noise in the water. Passive sensors become useless in shallow water environments because of the low Signal to Noise (S/N) ratio, so ASW operators favor active sonar and non-acoustic sensors there.

### 7. Sound Channels

In deep and shallow water, acoustic channels can form that essentially trap sound inside the channels. These channels can help propagate sound waves over very long distances and help relay a submarines location to a search vessel, but a crafty submarine masking its activities from prying hydrophones can also use them [9].

### 8. Other Considerations

The previously listed topics are by no means an exhaustive list of considerations. Some of the other major factors include: bottom composition (sand, clay, etc.), topology (sea mounts, pinnacles, trenches), and upslope/downslope effects. Bottom topology is important because it can impact the intensity of acoustic signals through absorption and scattering. For example, soft silt or clay bottoms will tend to attenuate sound while hard bottoms like rough rock will tend to reflect sound. By way of a common example, imagine talking in an enclosed room that is carpeted and then image the same room with a hard-wood floor. Topographical features, such as pinnacles, can reflect sound in ways that may be misinterpreted as submerged vessels. Further, the slope of the continental shelf can act like a megaphone, channeling sound from shallow water source to a receiver in deep water, thereby exposing a submarine that may not have been otherwise detected. This effect is referred to as down-slope enhancement in [9]. Signals originating in deep water may be picked up by receivers in shallow water and is known as up-slope enhancement or the "inverse megaphone effect" in [9]. These factors, and more, must be considered by both sides of an ASW engagement before entering the battle space.

## C. TOOLS OF THE TRADE

The right equipment plays an important role in ASW; from sonobuoys to towed arrays and on-board processors, the quality and sensitivity of equipment is important in influencing the probability of detecting a submarine.

### 1. Passive Sonar

Of all the tools available to the ASW practitioner, the passive options provide the most stealth and the most information. Classification of acoustic contacts depends upon having as complete of a picture of the soundscape as possible and can be broken into two phases: initial classification, and final classification. Initial classification is where a sensor operator is trying to determine if a contact of interest is/is not an aquatic animal or some other source of noise. To borrow a criminal justice example, it is like a police officer trying to establish "probable cause" as a pre-condition for follow on actions. In this example, the follow on action would be to continue target prosecution. Once probable cause has been established, the sensor operator needs to gather more evidence to get to the final classification, which is analogous to a detective having evidence that proves "beyond a reasonable doubt" that a submarine exists in the local area, but also who it belongs too.

Every submarine has an acoustic footprint, and a distinct acoustic signature. The acoustic footprint helps to divide submarines into families, but once a signature is detected, it is easy to identify an individual submarine. To complete this delicate task are two sets of sensors—passive sonobuoys and towed arrays. As detailed in [11], sonobuoys are a onetime use sensor; they are typically airdropped by helicopters and fixed wing aircraft, but can also be dropped over the side of a ship. The advantage of a sonobuoy is that it is cheap and expendable, and one can jettison many of them in the path of a submarine. They also have multiple depth settings that can be adjusted dynamically (one-way). The disadvantage is that they do not always work, have a limited battery life, and have limited transmission ranges and require multiple buoys in contact to establish a positional fix.

The other set of passive sensors are the towed arrays. Towed arrays tend to be more sensitive than sonobuoys, which allows for greater precision and higher quality data. This higher sensitivity results in greater detection ranges and bearings that are more accurate. Additionally, towed arrays can have their depth dynamically modified, as the depth of the towed body is often a function of the length of the tow line and the speed of the towing vessel. This allows the ASW practitioner to place their sensor in an optimum location. However, despite their advantages, they do have some limitations; namely, they are very susceptible to changes in movement, and will often require a period of stabilization before accurate data can be acquired following a change in course or speed. Additionally, due to sensor limitations and the nature of sound in water, there is an inherent amount of uncertainty in bearing information. This uncertainty is decreased by performing what is known as target motion analysis (TMA) as explained in [12]. Simply stated, TMA is a process by which many samples of data are acquired, processed, filtered. This information provides knowledge of the target's range, speed, and course and is used to create a fix and develop a track.

### 2. Active Sonar

If passive sonar tracking is akin to performing surgery with a sharp scalpel, then active sonar tracking is like performing surgery with a battle axe. Active sonar is great for many things, but being subtle is not one of them. Active sonar is best used when positional accuracy trumps tactical stealth; this becomes important when one is getting ready to launch a weapon, a weapon has already been launched by one or both belligerents, or one is trying to deter a weapons launch. Usually, the use of active sonar is considered an aggressive action, and one could expect it to be replied to in kind. However, it should also be noted that active sonar is also often used as a deterrent. While transiting choke points, shallow/littoral regions, or other areas where a potentially hostile submarine may be lying in wait, it is not un-common to see a screen of ships or aircraft out in front of the high value unit (HVU) pinging away. This action is not generally considered hostile, as it is defensive in nature. The threat conditions, intelligence reports, cultural norms, and rules of engagement (ROE) will typically dictate how the use of active sonar is likely to be interpreted. Actions that are considered hostile, aggressive, or annoying are largely a matter of opinion and motivation; careful consideration and good judgment must prevail when using this sensor.

Active transducers are installed onto many devices: hull-mounted sonars, helicopter dipping sonars, and sonobuoys are the prime examples. Regardless of their installation, they all work approximately the same. A transducer produces a pulse that travels through the water until it bounces off some object and returns a receiver. Time of flight and angle of incidence are computed to calculate a range and bearing [9]. Unfortunately, for the sonar operator, a ship, submarine, and a rock produce similar returns, and so they must have more information to decide which target is the one of interest. This is usually performed in concert with passive acoustic information, or information gathered from other sources.

### 3. Non-Acoustics

Non-Acoustics, as the name implies, covers the broad category of all the detection means that do not utilize sonic energy for detection. Radar systems are helpful in detecting submarines when they or parts of them like the sail or periscope are on the surface. IFF systems, the cousin to radar, are helpful in identifying unknown objects by sending out interrogation signals to receivers that return authenticated replies if they are friendly forces, or nothing if they are neutral or aggressive. Much like active sonar, most radar systems are not passive; their use can be detected by other platforms. Sophisticated electronic support measure (ESM) packages employed by many aircraft and maritime vessels serve as early warning and classification sensors. ESM systems are passive in nature and merely attempt to detect, classify, and gain bearing resolution on other active sensors like radar, IFF, and lasers. MAD systems attempt to detect submerged vessels by fluctuations in the normal/local magnetic field caused by the movement of a large metallic object. These systems are generally considered semi-passive as they do emit some radiation that could be detected. Electro-optical devices like FLIR and NVGs operate by being sensitive to infra-red radiation and are helpful for seeing dim lights at night or heat sources on or in the water. The human eye is adapted to detect movement and to perceive objects that appear out of place. Many submarines are spotted by the keen observation of aerial lookouts.

## D. GETTING THE MISSION DONE

The previous section discussed the sensors used against target submarines. This section focuses on the platforms that use those sensors.

### 1. Traditional Platforms

Until recently, the primary method of detecting and tracking submarines was through multiple manned platforms. Each platform is designed for a different phase in the ASW mission and usually covers a gap in another platform's capabilities. Starting at the furthest reaches of detection are the SURTASS ships. These ships, operated by the Military Sealift Command, have sophisticated acoustic sensors. Moving closer in is the Maritime Patrol and Reconnaissance Aircraft (MPRA) of which the U.S. Navy flies both the P-3C Orion, and its successor the P-8A Poseidon. According to [13], these aircraft have long ranges and can carry a large payload of sonobuoys, torpedoes, and mines and are often equipped with radar, MAD, and other non-acoustic detection devices. The P-8, in addition to new and upgraded sensors over the P-3, is also capable of in-air refueling, a higher service ceiling, and greater speeds than its predecessor.

Moving closer still are the destroyers, multi-mission surface combatants that are outfitted with powerful active sonar arrays along with sensitive towed passive sonars. Destroyers have long endurances and can travel at high speeds while carrying a significant amount of anti-submarine weapons. For clarity, when referring to destroyers, the author is specifically considering the DDG-51 family of warships. At the time of this document, the LCS/frigates currently do not have an operational ASW module and the cruisers are generally reserved for the Anti-Air Warfare role relegating ASW to a secondary mission.

Finally, patrolling the closest range to a subsurface contact is the ASW helicopter. Currently, the U.S. Navy only operates the MH-60R "Romeo" Seahawk for close range ASW. The Romeo's capabilities include: powerful dipping (active) sonar, a small complement of sonobuoys, surface search radar, FLIR, ESM, an ability to carry multiple torpedoes, and Hellfire missiles. The MH-60R is often deployed with surface ships like destroyers and cruisers.

### 2. New Platforms

Unmanned systems are increasingly being viewed as a means to improve detection of sub-surface contacts while achieving certain cost and operational efficiencies. The Navy hopes to achieve these goals through the reduction in associated manning requirements brought about by increased sensor coverage and increased persistence through endurance. Lower overall costs associated with maritime operations may be achieved by having dedicated platforms to conduct ASW that free up more expensive assets, such as destroyers. Many government and academic institutions are investigating the suitability of unmanned surface vehicles (USV) to perform all or parts of the ASW mission. The succeeding paragraphs discuss the two most mature ASW USV designs and their comparative strengths and limitations. These two designs exist on two opposite ends of the size spectrum and as such pose an upper and lower bound for future designs.

#### *a. ASW Continuous Trail Unmanned Vehicle (ACTUV)*

ACTUV, pronounced "active," is a large unmanned surface vehicle jointly produced by Defense Advanced Research Projects Agency (DARPA) and the U.S. defense company Leidos. Also known as *Sea Hunter*, she is 132 feet in length making it the largest USV to date. ACTUV boasts 60–90 day endurance while actively tracking a target. The vessel currently has two different types of sonars installed though the program is still in development and sensor packages are likely to change [14]. From an autonomy perspective, the most impressive quality is the suite of computers installed that allows ACTUV to autonomously follow maritime rules of the road and to track a submerged target without human intervention.

#### b. Sensor Hosting Autonomous Remote Craft (SHARC)

SHARC, pronounced "Shark," is a comparatively small unmanned vehicle produced jointly by Boeing and Liquid Robotics. SHARC is ten feet in length, has a four-foot beam, and has a free board of about one foot; the SHARC cuts a small profile. The SHARC is propelled by wave motion, and the sun powers its electronics. The SHARC has an endurance of up to a year with the limiting factor being salt encrustation and the accumulation of parasitic life. Because there are no motors, the SHARC is incredibly quiet. However, because it has no propulsion means other than waves, its forward speed is approximately 1–3 knots. This is its greatest drawback, though with careful planning, it can be mitigated. The SHARC collects acoustic information from its sensors and processes that information locally [15]. Table 1 compares SHARC and ACTUV.

Table 1. Comparison of USV Capabilities and Limitations

| Vehicle | Strengths | Limitations | Operation |
|---|---|---|---|
| **ACTUV** | High Speed<br>Long Endurance<br>Quiet<br>Multi-Sensor<br>Large Payload | Fossil Fuel Power<br>Large Size | Uses its dual sonars to detect, and track subsurface contacts. |
| **SHARC** | Low Observability<br>Very Long Endurance<br>Solar Powered<br>Wave Propelled<br>Very Quiet | Slow Speed | Processes and filters acoustic info onboard and notifies base only when a signal of interest. |

### 3. The ASW Detect-to-Engage Sequence

The ASW Detect-to-Engage Sequence is a way to think about an engagement with a potentially hostile submarine broken down into distinct phases that can loop back when there is insufficient data or clearance has not been received to proceed to the next phase. The phases are 1) detect, 2) localize, 3) classify, 4) track, and 5) attack. These phases overlap with parts of Joint "F2T2EA" Kill Chain Sequence contained in [16]. "F2T2EA" is an acronym that stands for Find-Fix-Track-Target-Engage-Asses. Members of other military branches may be more familiar with this concept and so it is included to facilitate understanding.

Table 2 is an illustration of how the ASW Detect-To-Engage sequence overlaps with the Joint F2T2EA sequence.

Table 2. ASW and Joint Operations Kill Chains Compared. Adapted from [16].

<table>
<tr><td>ASW DTE</td><td>Detect</td><td>Localize</td><td>Classify</td><td>Track</td><td colspan="3">Attack</td></tr>
<tr><td>Joint F2T2EA</td><td>Find</td><td colspan="2">Fix</td><td>Track</td><td>Target</td><td>Engage</td><td>Assess</td></tr>
</table>

## E. POTENTIALLY HOSTILE THREATS TO SURFACE VESSELS

### 1. Diesel-Electric Submarines

The most prolific submarine type operated worldwide, diesel-electric submarines are favored because they are relatively cheap to produce, hard to detect, and provide an asymmetric advantage (stealth) to the navy that employs them. However, for all of their benefits, these vessels are not without their drawbacks.

Traditionally referred to as 'conventional', the modern diesel-electric submarine has a lot in common with its predecessors that saw service in World War II. These vessels use diesel fueled combustion engines to operate their propulsion, drive their electrical generators, and to charge their batteries. The diesel engine is incredibly noisy and easily detectable acoustically, and usually requires the submarine to be frequently on or near the surface to vent combustion gases. Time spent in this configuration is minimized to the maximum extent because it makes the submarine vulnerable to air and surface assets.

The story is vastly different when considering this family of submarines when operating on battery. Like an electric car, a submarine operating on battery is very quiet, and may provide only the faintest clues to its presence, namely cavitation and fluid noise. These vessels generally lack the endurance found in the larger nuclear powered submarines; however, because of this, the crews of diesel-electric boats tend to be very familiar with operations in their local environment. This knowledge and proficiency coupled with their stealth make them dangerous.

### 2. Nuclear Powered Submarines

Much more expensive to produce because of the manufacturing and scientific costs associated with production, these types of ships only see service in the major navies of the world like the U.S., U.K., France, China, and Russia. Using fission reactors as a power source for propulsion, these vessels are much more expensive than diesel submarines to produce but are not limited by a need for frequent surfacing. They can stay submerged nearly indefinitely, constrained only by food reserves and crew endurance, making them a formidable threat.

These vessels are very quiet, certainly far more than conventional subs on diesel power, though they do have a critical vulnerability. The reactor aboard these vessels requires a constant flow of cooling water to keep the temperatures in the reactor from becoming critical. Flowing water requires pumps, and pumps make noise. To a keen ear, or electronic sensor, these pumps could be detectable

While conventional submarines generally lack the sustained speed required to trail or lead a target, the nuclear powered vessel has the speed needed to get ahead of many surface ships. This is a major consideration, as it allows the nuclear submarine commander to dictate the terms of an engagement, and frees them from having to rely on ambush tactics. Additionally, because of their comparative size, nuclear submarines also frequently carry nuclear ballistic missiles, sub-launched cruise missiles, and special equipment for irregular warfare purposes.

### 3. Submarine Weapons

This section discusses the means with which a submarine has to ensure that it is allowed a "vote" in an engagement scenario.

#### *a. The Crew*

It may seem a bit cliché, but a submarine is more than just a delivery platform for a suite of weapons and intelligence gathering tools. Each submarine is operated by a human crew and the vessel is an expensive instrument of national power. Therefore, not only are you fighting the weapons, but the collective intelligence of the crew who is driven by the same or similar motivations as our own sailors. The enemy is crafty, wants to be elusive, and likely fears defeat and death as much as any other person. The inherent strengths and weakness of the human mind are factors to consider when developing a system that is designed to defeat them.

#### *b. Torpedoes*

The torpedo is the submarine's primary close-in weapon and arguably its most damaging. Unlike missiles, torpedoes have significantly shorter ranges, but they carry much greater explosive payloads. There are many different types of torpedoes, to include wake-homing and sonar guided, but functionally they all have the same aim: get under the mid-point of a ship's keel and explode causing a massive air bubble to form under the ship that lifts it out of the water and breaks the keel. This cracking of the hull is devastating and will usually cause the ship to split in two parts. A USV designer should ensure that the vessel is able to detect a torpedo launch—a relatively simple task due to the distinct and easily discernible acoustic signature. Once detected a few options are available. First, the USV should immediately alert its controller, and all nearby assets of a torpedo launch. Second, if equipped, the USV should attempt to lure the torpedo away from its target by acting as a large counter measure. Third, and this may be more difficult, but the USV system as a whole might be able to plot the torpedo's track line and get a reciprocal bearing. While the torpedo will certainly create a wake that is highly visible during the day to an alert spotter, it would be nice to have more than a pair of eyes.

### *c. Missiles*

Submarines are capable of carrying an assortment of different missiles. For local defense while a submarine is on the surface, many navies will arm their subs with what are known as MANPADS, Man-Portable Air Defense Systems, more commonly referred to by the more popular brand name "Stinger." These shoulder fired weapons are intended to engage low-slow-flying aircraft, particularly helicopters that should get within their limited acquisition range. Moving up the lethality curve are the submarine launched anti-ship or land-attack cruise missiles. These weapons usually require external queuing sources or preset coordinates to be most effective. Finally, topping the scales on lethality are the ballistic missiles, which reach sub-orbital altitudes before their warheads are navigated to their targets. Ballistic missiles may carry conventional or nuclear warheads. Air assets are most at risk to MANPADS, surface ships are most at risk to the cruise missiles, and Carriers are at risk to ballistic missiles.

There is not much a USV outfitted for ASW can do about an incoming missile, but consideration should be given to determine how one might quickly increase the radar cross section or IR signature of the USV in an attempt to be a counter to an incoming missile.

### *d. Mines*

Other than directly attacking surface vessels, submarines are well adapted at laying down a mine field covertly. Nautical mines, like their land cousins, are nefarious weapons that often do not discriminate between their targets. Ocean mines can have multiple types of triggers. The most common are contact and induction triggers. Contact mines as the name suggests will not detonate until something physically contacts one of their fuses. Induction mines will either wait for a magnetic field to pass by releasing a mine to float to the surface and then detonate via contact or the magnetic field will be enough to set off the explosive. Mines aim to achieve a hard kill in a similar fashion as a torpedo, by exploding underneath a vessel thereby cracking its hull. Alternatively, a mine can be just as deadly when it punctures a hole in the side of a ship and causes compounding emergencies. For a modern example, see the USS Samuel B. Roberts case study in [17]. The “Sammy B” struck an Iranian mine that broke the keel and caused severe flooding and fires. It was only through the hard work of the crew that the ship survived.

Mines serve a strategic purpose by acting as a hazard to all maritime traffic. Mines are a convenient and economical way for an adversary to shape the battle space and political discourse to their advantage by creating choke points and barriers where none existed before. These obstacles can produce a funneling to maritime traffic that a submarine could use to its advantage.

Mine hunting has similarities with sub hunting, and it has been proposed in [2] that USVs could also be used as mine-hunters. More study would be required to determine if an ASW USV could serve double duty as a mine-countermeasure (MCM) USV.

#### *e. Counter Measures (CM)*

As if hunting submarines was not difficult already, the cat and mouse game that exists between the technology to hunt submarines and the sub’s ability to defeat or at least distract said technology is well known. In the zero-sum game of ASW, counter measures serve to give the submarine a few more moves before it is faced with a loss or can ensure a win. Counter measures include everything from low-tech static noise makers, to high-tech decoy UUVs.

The purpose of a counter measure is to deny the adversary the ability to gain a firing solution. If that action has failed and the enemy has fired a weapon, then CMs are used to try to defeat the weapon. The counter measure game becomes one of escalation where one side will develop a weapon to destroy their opponent, which drives the opposing side to develop a CM to defeat the weapon or targeting system. Then, as is natural, the initial side will then build into its software or hardware an ability to detect CMs thereby defeating them, and so on and so forth.

Understanding that subs may use CMs is important because it is likely that a USV will encounter them during the course of its service life. For example, a submarine, having been detected by the USV, might launch a CM to distract a USV before the USV can gain a better track or fix on the submarine. Think of it as similar to a magician's sleight of hand. The USV needs to know or learn the particular characteristics of CMs in order to ignore the misdirection so as to focus on the submarine's true signature.

# III. AUTONOMOUS SYSTEMS FOR ASW

Before one can begin to design an autonomous system, one needs to know a couple of key pieces of information. This document will not attempt to push any particular definition of autonomy but it is import for the reader to note that this is a contentious issue in the robotics field because the term ‘autonomous’ carries with it much weight from other fields of study like psychology, sociology, and philosophy. These groups have been trying to characterize autonomy in humans with varying definitions. This is a sticking point for the robotics community, as it is a relative newcomer to the discussion. Artificial intelligence comes to the proverbial table missing a key component—morality/soul/feelings, an aspect which is critical in the study of autonomy in humans, in a thought: “free will.”

Additionally, a distinction needs to be made between “autonomous” and “automatic.” The terms “autonomous” or “autonomy” refer to the agent’s ability to perform tasks with limited human involvement, whereas “automatic” or “automated” simply refer to behavior that is scripted and predictable given a certain start state. Algorithms are used to automate a system when much of the problem space can be covered by the algorithm. However, things become tricky when you begin dealing with many unknown and unpredictable behaviors.

The following sections lay out some concepts that are important to understanding autonomous systems in general and an ASW USV in particular.

## A. THE AGENT

The term agent is derived from the Latin word “agere” or “to do” [18]. Simply stated, an agent is an entity that performs actions. Certainly, this word may have an overly broad definition, though it is useful to use in place of pronouns. For the purposes of this paper, agent will refer to the high-level construct of the USV as a whole, understanding that this high level entity may actually be composed of sub-constructs of other agents, each with their own distinct behavior. The following sections discuss different aspects of an autonomous agent.

### 1. Artificial Intelligence

To begin to understand the limitations imposed on an autonomous system, it is important to remember that despite how "intelligent" it acts, it is still just software. At the risk of insulting our future robot overlords, this comment is not disparaging, but a statement of fact. When someone says that they have created artificial intelligence, they are saying that they created software or hardware that mimics the interactions that humans have, and in some ways is convincing enough that an outside observer might think for a moment that they are interacting with another human. This thought is the basis for the Turing Test. Alternatively it could mean that the software came up with the same or better solution than a human did given the same stimulus, as in a game of chess.

Alan Turing, of Enigma fame, is a legend in computer science. In 1950, Turing proposed a challenge: a computer with artificial intelligence as an attribute would appear to display human level intelligence under the certain conditions. The passing conditions were: after being given a set of written questions, the computer then independently composes written responses that an observer is unable to distinguish between human and computer. This test implies the need for optical scanning, natural language processing, and an extensive knowledge base from which to craft an answer [3]. This challenge was initially known as the Imitation Game and is now known as The Turing Test. The passing conditions for this test have been further refined and the test can be thought of as the high bar for any potential AI to meet. However, it is a bit limited in its scope and not all AI agents need to meet this standard.

### 2. Rationality

An action is said to be rational when it is performed to accomplish the best possible known outcome, emphasis on the word known. If there is uncertainty, or there is not enough time to make a well thought out decision, then an actor selects an action to support the best expected/projected outcome given the time and resources to do so. The later notion is referred to as limited rationality in [3]. The smart designer wants his or her system to be rational, following logic and rules, rather than choosing randomly, or knowingly choosing an incorrect move. It is important to stress that there may be an occasion that a rational actor needs to select an action at random, but this must be on purpose with the ultimate goal of achieving its objective. For example, a robot finds itself at a fork in a road, and knowing nothing of the paths that lay before it must select to go either left or right. If the robot is not allowed to back track, and must select either choice, then it may do so "randomly" and still be considered rational.

To help illustrate the point, Russell and Norvig suggest that rationality at any given point relies on four things, from [3]:

- The performance measure that defines the criterion of success.
- The agent's prior knowledge of the environment.
- The actions that the agent can perform.
- The agent's percept sequence to date.

#### 3. Sensors and Actuators

As mentioned in [3], sensors are used by an agent to perceive its environment. In the case of the ASW USV, sensors would include sonar, radar, cameras, GPS, and others as deemed appropriate. Actuators are anything that the agent uses to act upon its environment [3]. For this craft, its actuators will be its propulsion system, stability and helm (steering) control systems, communication systems, and if the USV were armed, the weapons systems could be considered actuators.

#### 4. Perceptive Sequence

Russell and Norvig define a percept in [3] as referring to the agent's perceptual inputs at any given point in time. Therefore, according to them, a percept sequence is the entire history of everything the agent has perceived up to that point in time.

#### 5. Agent Functions

An agent function is described in [3] as the mathematical mapping of any given percept sequence to an action. A table could be constructed to host every percept sequence (Ps) from Time = 0, till Time = n, but that table would grow very large, very quickly, growing without bound. In reality, one is only concerned with smaller slices of time in which interesting changes to the environment have occurred.

### 6. Agent Programs

The agent program is a counterpart to the agent function. As stated in [3], the agent function is an external observation of what the agent has done, while the agent program is what is actually controlling actions at each instant in time. The agent program is the internal programming that is responding to stimulus and performing an action. Once the action has been completed, the precept sequence that resulted in that action could be logged in the agent function.

## B. THE ENVIRONMENT

The term environment needs some disambiguation. First, for the purposes of this document, consider the term 'task-environment' to refer to the problem space that the USV is a solution too. This task-environment also includes the physical and or virtual environment, but those will be discussed separately. Russell and Norvig recommend the following acronym, PEAS, for defining the Task Environment. The following list is adapted from [3].

- P – Performance Measures – quantitative metrics need to be defined for the agent to determine how successful it is in a given environment. In the case of USV, measures might include: Minimum travel time between waypoints, minimum fuel usage, minimum COLREGs violations, and minimum false positives.
- E – Environment – this is the physical (or virtual) environment that the agent is operating in. For the ASW USV, this environment would include other surface and subsurface vessels, hazards to nautical navigation, underwater topography, maritime traffic separation schemes, and sea state – to name a few.
- A – Actuators – as previously mentioned, these are parts of the vehicle that interact with the outside world. Examples: Rudder controls, engine throttle, trim servos, navigation lights, external interface panel/touch screen, etc.

- S – Sensors – as mentioned, these are the instruments and sensors the vehicles uses to perceive the environment. Examples: Fathometer, GPS, compass, radar, electro-optical devices (infrared, true color), sonar, etc.

## C. THE PROBLEM

The previous sections discussed the submarine threat, its capabilities, the underwater environment, artificial intelligence, and autonomous systems. This serves as the framework for the real design challenge.

### 1. Protecting the Battle Group

The United States Navy has identified the following area as being suitable for employment of USVs: peacetime ASW in performing the Maritime Shield and Protected Passage missions from [1, 2]. These missions serve to push out the battle groups sensor net to expand the area at which a high value unit (HVU) like an aircraft carrier may operate free from harassment by submarines. This problem does not concern itself with attempting to detect all submarines in the ocean, or trying to follow submarines from their homeports. Battle group protection is about forming a perimeter around the HVU that, with reasonable probability, is clear of undetected submarines. The crew of an undetected submarine has a significant advantage over their opponent—surprise. Once the submarine's crew knows they have been detected, their advantage of surprise is diminished, and hopefully they feel that the risk of a successful counter attack would be too great as to be too risky their safety.

### 2. Two Scenarios

As mentioned, two scenarios are being considered: maritime shield and protected passage. Both of these scenarios are centered on the HVU, but one is stationary (Shield) and the other is mobile (Passage). The two mission areas are shown in relation to each other in Figure 2.

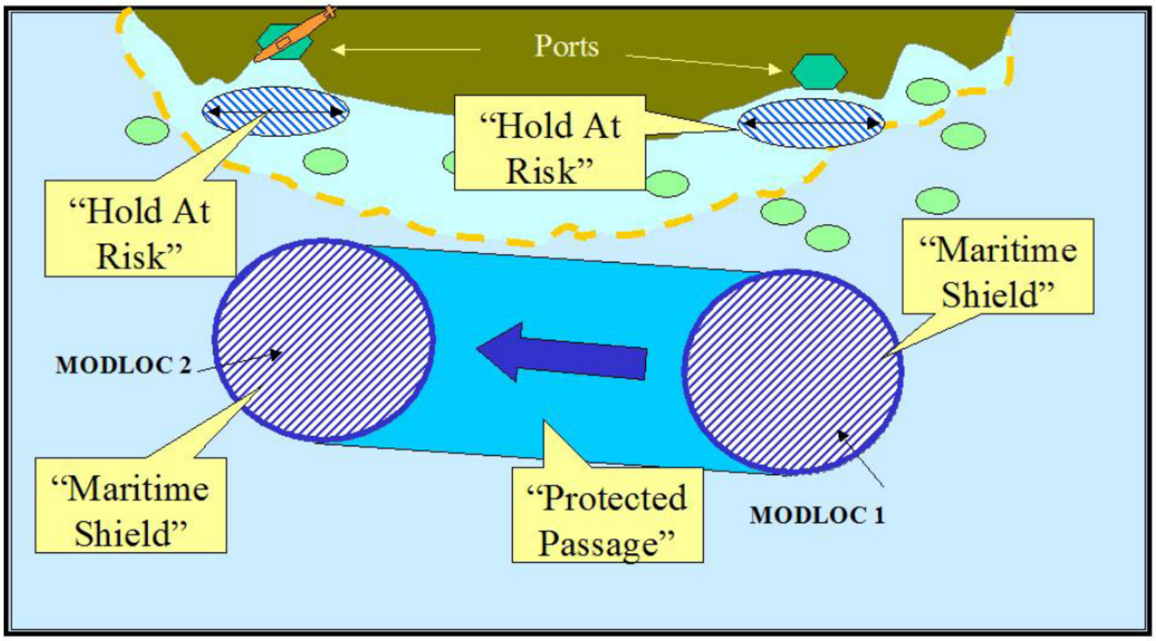


Figure 2. ASW Nomenclature. Source: [1].

Maritime Shield is focused on protecting the MODLOC or CV (Carrier) Operations Area (CVOA), that body of water that directly surrounds a HVU where the HVU will be operating for an extended period of time. Traditionally this body of water is laid out as a square with the HVU at the origin, though it could also be a circular shape out to some radius from the HVU. No matter the geometry, the shape remains stationary even though the HVU may be moving inside. The HVU is vulnerable because after a few days of observation, an adversary may be able to suppose where the HVU is or will be and take steps to neutralize it. Having early warning of a perimeter breach is important to prevent this situation. This mission is illustrated in Figure 3.

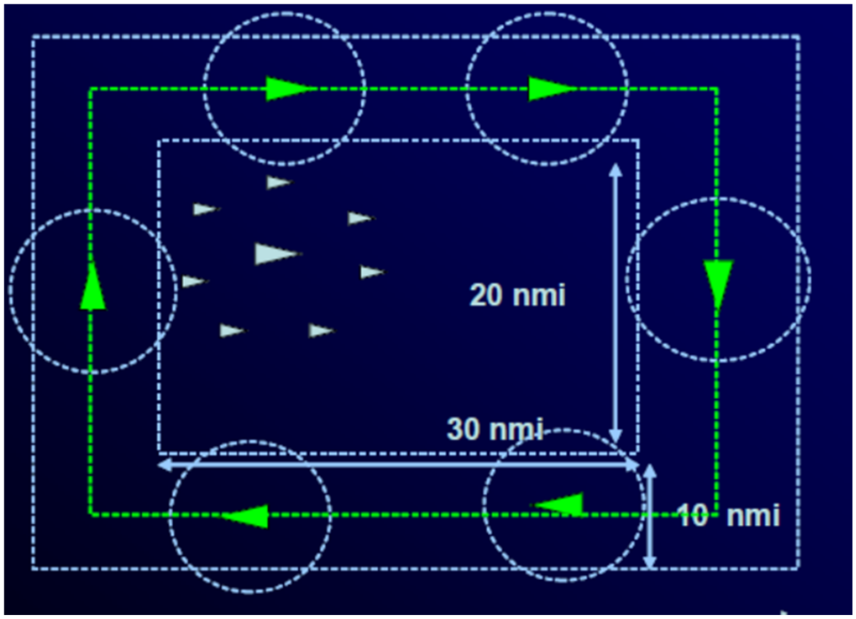


Figure 3. Example of Maritime Shield. Source: [1].

Periodically, it is necessary for the HVU to reposition itself, sometimes hundreds of miles away to another MODLOC/CVOA. In this situation, the HVU becomes vulnerable to an ambush or a flanking maneuver. When the HVU is in transit, it becomes susceptible to attack from a submarine that may be lying in its path, like a coiled viper, to strike as the unit passes overhead. Similarly, the HVU could possibly be funneled into a kill box composed of a well-placed mine-field or potentially hostile SAG. Furthermore, the HVU is concerned with the reach of land based area denial weapons, of which the adversary is well acquainted with the ranges and therefore limitations, and could attempt to push the battlegroup into this range. If the HVU avoids possible ensnarement and traps, it may still be vulnerable to attack while its figurative back is turned. The baffles are a well-known region behind a ship where its acoustic sensors may not function very well. A submarine can exploit this region to sneak up behind a ship and fire a weapon to follow the ship's wake. Delousing, as it is called, is the part of the mission in the vanguard where units are actively trying to "push" submarines out of the intended travel path. No special term exists for covering the rear, but it is just as important that someone does not sneak in from the sides or rear flanks of the formation. This mission is illustrated in Figure 4.

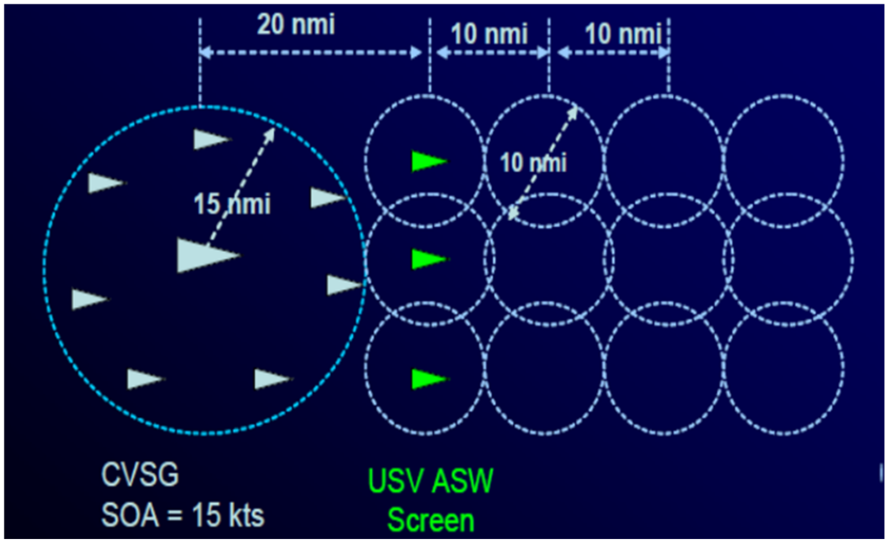

Figure 4. Example of Protected Passage. Source: [1].

### 3. A Note on Complexity

In the information sense-making process, there is a model known as the Cynefin framework that helps form a discussion on systems. In developing the software architecture for a USV for ASW, it is important to understand what kind of problem environment one is dealing with to ensure that developed solutions are likely to fit. In this model from [19], five domains exist (in order of increasing complexity): simple, complicated, complex, chaotic, and disorder. Simple systems are those that have a strong cause and effect relationship and information is ordered. Complicated systems have a recognizable cause and effect relationship, but may require some analysis to discover it. There may be multiple "correct" ways of solving a problem, but it hinges on an expert's experience to select one that makes sense. In a complex environment, cause and effect are obvious post hoc with only light constraints on agents. A chaotic environment has very little order and any decision is probably as good a decision as any other [19]. Finally, disorder has no useful structure. D. Snowden, the author of the Cynefin framework, states that disorder is the natural state that most people and environments are in until they have been better understood and can start working from one of the other domains.

While it would be nice to claim that non-wartime ASW could be considered simple that would be a flight of fancy. This author's assessment is that this phase of ASW falls somewhere in the complex or complicated regions of the model. For a moment, suppose one eliminates some of the variables about acoustics in the open ocean and assumes a constant speed and therefore highly predictable nature for sound propagation. This assumption would alleviate much complexity, but one would still be left with the human component. One could attempt to make assumptions on human behavior, but those assumptions should be characterized as foolish at best and deadly at worst. For example, one might assume that all submarines from allied countries are friendly and all submarines from non-allies are potentially hostile, and this is probably an assumption that most commanders make…but it is flawed, as friends can quickly become enemies and enemies may not always attack.

Suppose one were to assume that a submarine belonging to a country called Orange is detected close to a high value unit of a country called Blue, then that submarine is considered potentially hostile by Blue. This is a fair assumption from the defensive standpoint of Blue, it does not hurt to think that a submarine belonging to a potential foe (Orange) might attack without provocation; after all, one is only a bullet or torpedo away from a war…. Therefore, Blue takes appropriate defensive measures in accordance with ROE and doctrine. For the Trekkies (Star Trek fans), this would be the equivalent of setting "Yellow Alert." Now suppose that it is observed that Orange's submarine has come to periscope depth, radiated radar, and has been acoustically detected opening torpedo or missile tubes. Blue is now faced with a hard choice, does he attack Orange preemptively before Orange has shot a weapon, or does he wait…knowing that only the utterance of the word "Fire" stands between a warhead and Blue having to defend himself? Both actions have risks and consequences. The answer is…it depends, and that is why a ship's captain is paid the proverbial big-bucks to decide. This scenario is given to hint at the inherent complexity of just the human element, let alone the physical environment. When taken in summation, ASW in non-wartime can best be classified as a complex domain.

You might be wondering, "Why is this important?" The proposed USV system must operate in this environment, and it is vitally important to engineers, programmers, operators, and policy-makers to understand the inherent limitations imposed by such a dynamic situation. It will be impossible to make a USV that operates perfectly in all situations, as it is practically impossible to predict every possible action and reaction that every agent will make, especially agents that may not always be acting rationally. Instead, the user of this system must be satisfied with a system that is limited in scope, ability, and applicability, and therefore must craft the test and verification cases carefully to ensure proper operation for the most critical of functions.

In other words, rely on a USV to provide information that informs the decisions and actions of humans. The challenge is to anticipate what information skilled users will need to make good decisions.

# IV. DESIGNING A SOLUTION

On the surface, maritime shield and protected passage may appear to be completely different problems, sharing only a common operational area. However, the more one considers it, the more it becomes obvious that from a software perspective, the scenarios are close enough to each other that a common solution can be developed. However, there is a strong caveat—while the software may be identical, the hardware probably will not be. Both mission sets share many traits; however, Protected passage favors a vessel that trades endurance for speed based on a need to stay with or ahead of an advancing HVU. The maritime shield mission, being one where the HVU lingers in an area for a considerable amount of time lends itself to a design that conserves energy and requires minimal interaction with support vessels.

A note on employment: it should be considered that a blended/hybrid use of both of these types of platforms will likely yield the most defensive advantage to the HVU. A protected passage hull form would have speed enough to traverse the near-mid range areas around an HVU to quickly prosecute any strange readings that a Maritime Shield hull form detects. Instead of trying to engineer a solution that fits all scenarios (poorly), it would be wiser to design two dedicated platforms that execute their respective missions exceptionally well, and then use them in concert with each other to minimize their disadvantages while capitalizing on their advantages. To be succinct: keep it simple, have defined roles, avoid multi-mission, and realize that mission creep is inevitable.

This chapter is organized in the following manner: Sections A through C are the preliminary sections that set the framework for a discussion. Sections D and E outline the design while Sections F through I discuss each major module.

## A. REQUIREMENTS ANALYSIS

> The purpose of requirements analysis is to determine a customer's needs in sufficient detail to plan the construction of a software system meeting those needs. [6]

In this section, the requirements of an ASW USV are detailed. Few of the requirements have been stated explicitly, many have been stated implicitly. A larger number still have been derived when taking the implied and explicit requirements to their logical conclusions.

Problem statement: The purpose of the shipboard ASW USV control system is to enable a single operator or a team of operators to manage one-to-many USVs in support of ASW operations in the vicinity of a HVU and its escorts.

This is a plain language statement from the perspective of the customer [6], in this case the U.S. Navy, which will guide the rest of the development process. The vagueness of the statement is a result of the vantage point it was made from, we will call it the thirty-thousand foot view. At that altitude, everything is tiny and imprecise, but it will be necessary to break this statement open to further define requirements and to build a model that integrates all the requirements.

## B. ASSUMPTIONS

The following is a list of the initial planning assumptions on how the USV system should operate:

- The USV will not be used as a weapons delivery platform.
- The USV will not be regularly operated in known combat areas. Self-preservation, passive defense measures only
- The USV will likely be used in partially, but not fully degraded communications environments.
- Near-Real Time C2 is sufficient; some latency in the receipt and execution of commands to USV is permissible.
- The USV is not intended to be a replacement for any current system, but rather an augmentation to existing platforms.
- The USV control system will be able to be installed aboard LCS or larger warships.

## C. SETTING THE AUTOMATION BOUNDARY

For the scope of this project, the solution space is defined as starting from an individual USV, proceeding to a central command module, and terminating with an end user. Integration with other existing systems will be discussed as necessary, but further study into integration will be required before adoption of this system. Setting the automation boundary functions similar to stating the scope of a research study; it identifies what is and is not inside the responsibility of the automated system, as illustrated by Figure 5.

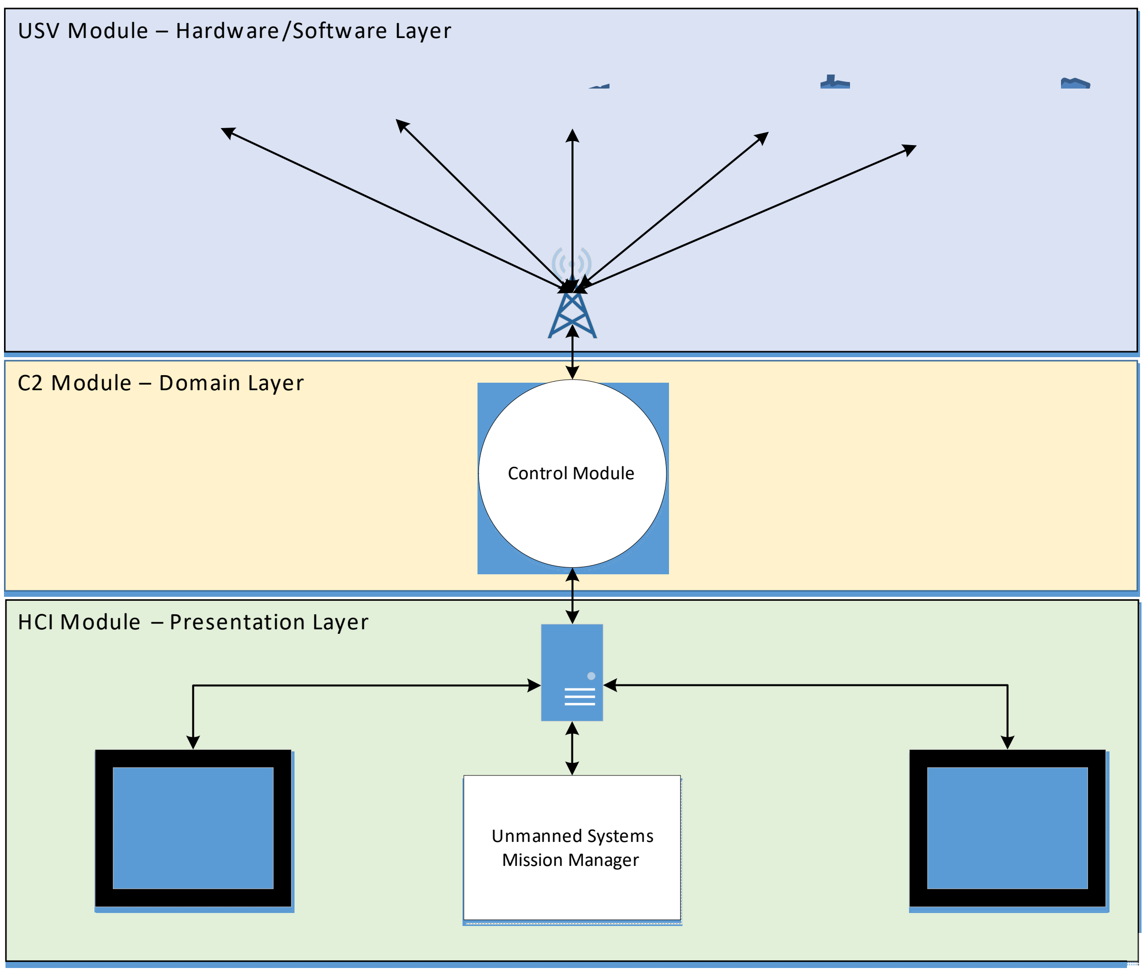


Figure 5. Automation Boundary

## D. DESIGN AND ARCHITECTURE

This system is composed of three distinct software components that together form one system. These components are the USV module, command and control (C2) module, and the human computer interface (HCI) module. In the following paragraphs, the thought behind each module is explained as well as the considerations for each module.

The design for this system is influenced by the desire for simplicity and modularity. The goal being to avoid a monolithic structure that becomes difficult to modify and manage. Additionally, the design follows a classic three-tier approach as suggested by [20], where the USV encompasses the hardware/software layer, the C2 module encapsulates the domain layer, and the HCI module encompasses the presentation layer. Each layer is functionally separate except for the needed cross layer connections. This approach supports the modularity aspect, and allows changes made to aspects of one module to have minimal to no impact on other modules. The main goal here is that if one wants to repair, replace, or add functionality to the HCI module, it should not "break" anything in the C2 or USV modules and vice-versa.

The hardware/software layer is concerned primarily with controlling the hardware that is aboard each USV, and with converting raw sensor outputs data into digital data that can be more easily shared and manipulated. The domain layer as discussed in [20] is concerned primarily with managing the business rules of ASW, remote vessel operation, and acting as a clearing house of information to be used by the presentation layer. Finally, the presentation layer is concerned with displaying information to the end-user and capturing the user's input to control operations. In a tiered architecture, the lowest layer has very little awareness of the higher layers, it simply does what it needs to do and keeps operating until it is stopped. As one ascends layers, their awareness grows but their influence on lower layers diminishes.

- The following list has a brief overview of each module before the more detailed descriptions that follow
- USV Module – Primarily a data gathering and limited information-production agent. This module performs many "housekeeping" functions associated with an autonomous vehicle. Its primary objectives are to go

where instructed, not run into things along the way, operate onboard sensors, and if necessary-follow assigned targets.

- C2 Module – Data and information fusion agent, keeps track of USVs so that humans do not have to too. Produces info to be consumed by HCI module or other consumers as required.
- HCI Module – Information presentation and human input gatherer. Produces no new information.

## E. AREAS FOR AUTOMATION

The purpose of this section is to discuss areas that can benefit from automation or refinement to present automation if already automated.

### 1. Detection

Detection is arguably the most important part of ASW; it is the point from which all other actions are measured. If one does not detect anything, then they need to keep searching until they find something or they are directed to cease searching. To return to the discussion on complexity, ASW before detection could be classified as disorder or chaos, the equivalent of watching the static on a television looking for an image to show, even if just briefly. Granted, one usually does not perform ASW unless there is a reason to suspect that there might be submarine activity, after all there are other threats that could impact the mission far before a submarine does. The battle group commander has limited human and vehicle resources and so he must be wise with the expenditure of effort. However, even when a commander has established an ASW watch team, there is no guarantee that an adversary will show up. When this occurs, it leaves the watch-standers fixed at their stations hoping to see something interesting.

This is a waste of human resources, to dully sit and watch a screen until something interesting appears or until the ASW team gets better queuing information. This then becomes a candidate for automation, but one must be cautious—unless a search algorithm is properly configured, the operator may be inundated with false positive alerts. This is where an artificial neural network (ANN) may show its true potential. By using the ANN with a search algorithm, a search program could comb through data sets collected from the USVs in near real-time through offline processing. While the information would be time-late, it would help to establish a high probability that a contact of interest (COI) exists in the search region. It may even be possible to establish an initial position, known as a datum. This is helpful because an area of uncertainly can be plotted from that point. By using heuristics and simple reasoning, operators may then be able to place sensors in the water that will yield more information.

Detection requires a low false positive rate because the sensors that would be used to investigate a possible contact are expensive to use with respect to time, and unit cost.

### 2. Localization and Tracking

Localization, also called fixing, is the process by which an initial position estimate of the target is obtained and follows after detection and dovetails into tracking. Localization is the step in ASW after initial detection where the team attempts to establish a Datum or a follow on fix from a Datum. Once course and speed have been established for a contact the team moves on to tracking i.e., the process by which a fix is updated as the target moves.

#### *a. Considerations*

While signal processing is quite robust aboard current ASW assets, it is still policy to require a human to evaluate the presented information to create an initial line of bearing to an underwater contact. After obtaining multiple lines of bearing, a positional fix can be established for initial target tracking. At this point it is possible for an operator to hand over tracking to the computer, and they often do. However, the wise operator will also continue to maintain their own track of a target for backup.

Current tracking algorithms generally function well; however, they do not perform well with minimal information or time-late information. As a result, the area of uncertainty around automated tracks may grow quickly when “fresh” contact information is unavailable. Many tracking algorithms use a form of least-squares regression to plot track-lines. These track-lines can become skewed when junk information is supplied. The phrase “garbage in, garbage out” is common when discussing such algorithms. A human operator is not as easily fooled by tactics that a submarine may employ to throw off a hunter and is usually more selective about which data points are incorporated into their tracking solution.

Improvements to the automated tracking algorithms would greatly improve the accuracy and reliability of the generated tracks. It would be helpful if the system recommended a location for the next buoy drop, or where to position a USV.

#### *b. Implementation*

Tracking the submarine should be performed by the C2 module, as it will have the best SA of the mission and all the other moving parts. However, the vehicles need to be adept at knowing where other USV's in the group are so that each can benefit by collective track processing for the same contact.

This task is more complicated than simply updating the fixes from acoustic sources to come up with an accurate track of a contact. This task would ordinarily require the placement of more sonobuoys in the predicted path of the submarine, but if the USVs could sprint ahead just a few hundred yards, then they themselves would be able to form a tracking chain. To accomplish this will require a few key enablers: each USV group needs to know where its neighbors are for collision avoidance purposes, and to ensure placement in a logical spot. The USVs may not know which vehicle has the best contact with the submarine, so it is therefore contingent upon the C2 module to track this information and ensure that only those vehicles that are down Doppler with increasing integration times are repositioned. Additionally, this will require the USVs to be able to communicate with neighbors to share acoustic data relevant to tracking.

### 3. Dynamic Event Notification

In the ASW lexicon, a dynamic event is an acoustic event of significance with the following examples: speed change, course change, depth change, or CPA on a sensor. These events may register as a shift in sonic frequencies observed (Doppler shift), a sudden increase or decrease in volume of a sound source, or even a complete loss of a signal. These events are of such importance that the operator needs to be alerted immediately when one occurs. Initially, a dynamic event will be observed on the USV, which will send a notification to the C2 module which will then generate the message for display through the HCI module.

### 4. Contact Classification

Assigning a classification to an underwater contact is a labor intensive process. The process begins at initial contact, where an operator attempts to make an early decision if the new acoustic contact is biologic or not biologic. This is important because it is a waste of time to track whales, dolphins, and schools of fish. Next, a human operator needs to decide if the contact is something on the surface, something in the air passing overhead, a fixed shore based facility, etc. Next, once it has been decided or determined that the contact is likely to be a submarine, it is then necessary to determine who it belongs to. As a matter of practice, the U.S. Navy prefers to minimize the amount of time spent tracking their own submarines, as presumably the submarines know where they are. There are multiple channels to do this, but usually a quick chat with the Submarine Operating Authority (SUBOPATH) will eliminate the possibility of expending wasted effort. SUBOPATH is responsible for knowing where friendly submarines are operating. Once a submarine is determined not to be an ally, the process of attribution begins. While this may still seem like a long list, and it is, there are only a few major variants of submarines that have been exported or developed elsewhere. The arduous task now becomes matching the signals observed to known or predicted signatures.

This task is ripe for automation, but it requires the C2 module to have access to ACINT databases, SIGINT databases, and as many rich and varied data sources as is possible. Additionally, it requires quite a bit of experience and expertise in making accurate attribution decisions.

### 5. Signal Processing

Currently, signal processing is already heavily automated, with the acoustic processors on-board the MH-60R “Romeo” Seahawk and P-8A Poseidon performing much of the heavy lift. Using beamforming techniques, along with different filters and amplifiers, signal processors clean up a lot of the noise in the underwater environment before it gets to the human operator. The human operator then fuses the information displayed with their knowledge of submarine TTPs and knowledge of what separates a sub from surface vessel or a whale. A sensor operator is looking for Doppler shifts in frequencies as well as bearing shifts to indicate some sort of dynamic event. These two particular events would usually correspond to a contact reaching its closet-point-of-approach (CPA), or changing direction.

### 6. Navigation

When discussing navigation, it is important to be explicit because there is a decided difference between finding the shortest route between two points and successfully moving though the real world to get there. When most people think "navigation" they think the latter, but programmers can often mean the former. The procedure to find the shortest route between two points is not a trivial problem for computers to perform. In fact, some of these problems fall into the category of NP-Hard and NP-Complete problems. A well-known computationally challenging example is the traveling salesmen problem (TSP). The TSP is an optimization problem where one is given a list of cities and the distances between each pair, with the request to find the "cheapest" route [21]. Cheap may be in respect to time, distance, or some other optimization factor. This is a seemingly simple problem, but can become quite computationally intensive. To avoid the computational complexity issue, heuristics have been developed and there are known solutions to specific instances of a TSP. A USV is likely to face routing problems, especially in constrained waters like inland waterways and navigation channels.

Autonomous navigation is a tough problem because it requires quite a bit of information to be seamlessly fused, the least of which is the geographic path, and appropriate decisions made. In addition to the route planning problem, navigation is not considered successful until an agent reaches their objective. This requires the agent to maneuver around any obstacles that might be in their way. There are many tools with which to detect objects, and the selection of those tools will depend on the tolerance for errors. Radar and sonar are great tools for getting gross estimates to targets, but there is an inherent amount of imprecision in these sensors. This imprecision increases as one considers dynamic motion for both the interrogator and the interrogated. Lasers are great for obtaining very accurate distances, but their range is limited by line-of-sight as well as atmospheric obscurants like dust and moisture. GPS is another great tool that can provide high precision and accuracy, but it carries with it a significant vulnerability if it is the only instrument used in navigation. Additionally, GPS allows the user to resolve their position to a point with a small area of uncertainty of only a few yards/meters.

Once an agent has accurately resolved their current position on the globe, and identified obstacles to avoid, the task of navigation is almost complete. Humans have developed complicated sets of rules to govern the safe and orderly conduct of maritime traffic, which are encoded in the following example publications: International Maritime Organization's (IMO) Convention on the International Regulations for Preventing Collisions at Sea (COLREGs), the U.S. Coast Guard's *Navigation Rules and Regulations Handbook*, which is commonly referred to as "the (maritime) rules of the road" that govern traffic inside U.S. territorial waters [22], and UNCLOS. This is not an exhaustive list but serves as a functional example. In order to increase the autonomy of a USV it is necessary that the vessel complies with the rule sets, understands when there are conflicting rules and can resolve contradictions and situations where other vessels are not following the rules.

DARPA advertises the ACTUV/Sea Hunter as being able to comply with all these regulations, but aside from this example, most other commercial and military programs still lag behind in this area. In order to accomplish this feat, advanced artificial intelligence is required to be able to internalize the human rules, and make appropriate judgments to dictate movement decisions. This research area is still open for development and advancement.

### 7. Formation Movement and Station Keeping

Formations of vehicles provide advantages over loosely coupled or unsynchronized single unit operations. A formation, by its nature implies that vehicles are in closer proximity to each other than is considered normal or safe. The burden to define what constitutes "normal" and "safe" is left to specific domains. Speaking in general, as the proximity between craft decreases, the probability of a collision increases. A collision at sea or in the air is considered a severe consequence due to the potential for loss of life or costly damage to equipment. Therefore, formation operations are considered to be higher risk evolutions than non-formation ops.

The increase in risk from operating in formation is mitigated through close coordination and standardization of movements. Additionally, the risk is outweighed by the benefits of operating in formation. This assessment is task dependent and is not appropriate in all operating conditions. The benefits from operating in formation include: easier control of many units through clustering/abstraction, division of labor and responsibilities to other formation members (like navigation or communication), as well as mutual support and overlap of sensor coverage. The sub-task of maintaining a relative position with respect to a guide is known as station keeping. Station keeping is a concentration intensive task for humans due to the need to constantly adjust a vehicle's movement in order to remain in a designated position. The intensity of this task is relieved by increasing the separation between individuals.

By acknowledging the risks and the challenges of formation operations, employment options are increased. Operating USVs in formations allows for a single human to control more units than if they were to try to control them as individuals. This abstraction is what will allow the savings in manpower that is sought.

## F. THE USV MODULE

An overarching design philosophy for the USV software is the Keep-It-Simple-Stupid (KISS) principle. When software gets bloated, it becomes hard to maintain. The developer should ensure that the software that runs aboard the physical platform is kept to the essentials. The definition of "essential" is task specific, though for this problem the following are considered essential: propulsion and steering control, navigation and obstacle avoidance, communication link to control entity, and of course, sensor interfaces.

The advantages of adhering to this mentality are that it makes the job of maintaining a code base easier, and it simplifies the process of adding future functionality. A. Oliveira in his dissertation [5], titled conspicuously “Software Architecture for Autonomous Vehicles,” runs with this idea of simplicity. In the report, he provides a clean technical outline of the software for an unmanned surface vehicle for use in commercial ventures. Many of his ideas influence this work, as there were some critical insights that were beneficial to this project.

Two reports of interest, [23] and [24], detail the efforts of multiple computer science students to formulate software requirements for a USV. In [23], a group of students taking a software methodology course offered by Dr. Berzins at the Naval Postgraduate School (NPS) approached three different ASW employment contexts: littoral operations, carrier strike group operations in deep water, and theater-wide ASW. The findings of the six groups that participated were condensed into a single set of requirements that represented a general set or requirements for an ASW USV. The following year, a second study as described in [24] tackled the same design challenge with a tighter scope. Two teams each, for four teams in total, worked on the maritime shield and protected passage sub-mission sets of carrier strike group operations in deep water. The requirements generated by the student groups were again consolidated. The designs were also briefed to experts in the field of ASW and the feedback of these experts as captured in the report. Both of these studies were sponsored by OPNAV.

To avoid a duplication of effort, this thesis uses the feedback provided by the subject matter experts to inform the design of the C2 and HCI modules. It should be noted that none of the students that participated in the second study had any experience with ASW. With only a brief introduction to ASW, and in the reading material that is openly available online, the students were still able to design software architectures without any bias towards what a solution might look like. While their designs were insightful, given their lack of familiarity with the domain, there are some oversights. The following sections seek to address those shortcomings.

### 1. Hardware Interfaces

First and foremost, [5] recommends keeping the software independent from the hardware and that the choices in components should allow for all current and future interfaces. This recommendation recognizes a key characteristic of software and autonomous systems—change. It is important that future operators have the ability to upgrade sensors, or to modify the code without breaking the entire system. To do this sensibly, one needs to select or specify hardware that has standardized external interfaces (ex: USB, IDE, RS232).

### 2. Operating System

Each USV, regardless of variant, will have an operating system (OS) loaded on it. In the absence of guidance relating to operating systems, a LINUX based operating system is recommended. In comparison to other operating systems, a Linux base allows for more customization, which has many benefits. First, a developer can trim parts of the OS out that are not needed for the operation of the USV. This adheres to the minimalist principle recommended in [5] while presenting a smaller attack surface towards a potential cyber-attack. An advantage to using the Linux OS is that it treats everything from a DVD player, a file folder, or a desktop monitor as a file. For the uninitiated, this is a benefit because sensors, actuators, as well as any number of devices can be addressed as a file by the file system. This is in contrast to other operating systems that treat these objects differently. Ideally, this ease of use will also allow for easier code maintenance.

Different hull variations will have different equipment, capabilities, and limitations. Fundamentally, the software does not care about the differences in hardware, so long as an OS is chosen that allows for easy device driver configuration, also known as Plug-n-Play. On startup, the OS will poll all connected hardware, determine what is installed, load the appropriate device driver from a library, and then set its internal state to register the new limits. For instance, if the vessel is commanded to transit at 20 knots, but the hardware is incapable of supporting that speed, then an exception will be thrown and reported to the C2 module.

### 3. Outgoing Communications

To keep things simple, there are only three categories of data that should originate from the USV. The first category is monitoring and control (MC), the second category is sensor streams (S2), and the third is group coordination (GC). Limited communication resources (time, bandwidth, frequencies) imply a need to keep the size and quantity of data packets to a minimum. The divide between MC and S2 is intended to separate the generally smaller sized but more numerous MC messages from the larger S2 streams. Also, it will be necessary to be selective about which USVs provide S2 data. The first two categories of data communication are transmitted by the USV back to the C2 module while the third category, GC, is only communicated between USV members operating in a group. These messages are used to de-conflict travel paths, share contact information, and to maintain formation stations.

MC data will consist of all the administrative communications like acknowledgement of packets, sending of status and position reports, and warning notifications. Warning notifications are those messages that signal to the C2 module and the HCI module that there has been some error aboard the USV that requires attention. Some errors will only need to be logged; others can be taken care of between the C2 module and USV, with the remainder requiring human intervention. Obviously, the messages that require human actions should be limited to only the most important, so as not to inundate the operator.

Because of the nature of the S2 data, it is important to allocate a "thicker pipe" to this source. However, at no time can the MC data be neglected, so it must always have a dedicated link for each USV. A communications engineer will need to identify the most appropriate communication protocol that allows many units to realize virtually synchronous communications. However, lacking the expert guidance, the recommendation is to use a protocol similar to TCP for MC messages, and RTMP for S2 streams. In the case of MC messages, it is important to know that the C2 module actually received the message, and a TCP like protocol will provide this verification. In the case that a message was not received, after some time-out period, the USV would resend the message until it received an acknowledgment. For the S2 streams, this kind of verification is unneeded but not unwarranted. Use of RTMP allows for similar kinds of handshakes that occur with TCP, but it is optimized for pushing larger chunks of information. RTMP allows for the transmission of live broadcasts as well as previously recorded productions as specified in [25]. Streaming services like Livestream and YouTube use RTMP for their live streaming data [26]. RTMP allows for recording of the stream as well as each chunk of data has its own unique identifier that allows for a reconstruction of data.

#### 4. Incoming Communications

The only pieces of data that should be coming to the USVs are instructions/commands from the C2 module. Instructions are sequences of commands that are issued to the USV for execution. Some instructions are to control the sensors and their settings, others will be for updating navigation waypoints, and still others will be used to dictate actions in the case of an emergency. Just like the outgoing communications, these messages will need to be decrypted before they can be delivered to the necessary element. The instructions will still need some routing once aboard the USV, but is taken care of by the operating system.

### G. COMMAND AND CONTROL MODULE

The Command and Control (C2) Module is the brains of the operation, working to ensure that there is a seamless connection between the human user and the USV. At times the C2 module operates as a traffic cop, directing information between the two parties, other times it needs to act as a synthetic member of the team. In situations where the human lacks in computational and logical reasoning, the C2 module attempts to overcome this shortcoming. Think of the C2 module as Mr. Data to the human operator Captain Picard from the popular television series Star Trek.

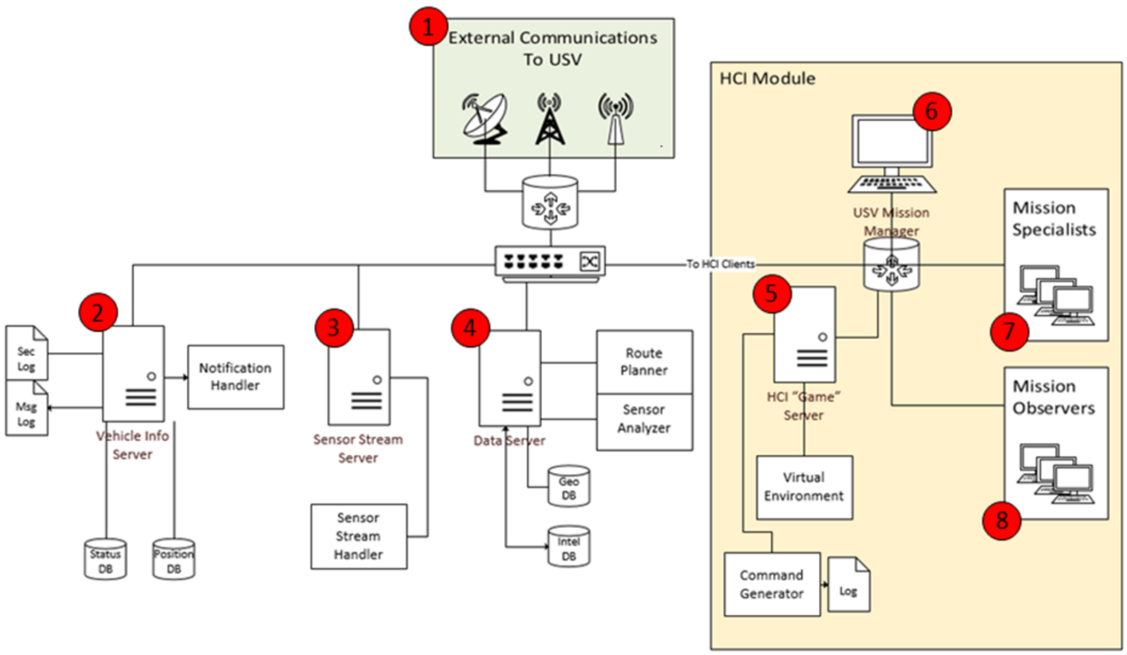


Figure 6. C2 and HCI Modules

### 1. Use Case

This section refers to the red numbers on different components in Figure 6. Referring to the numbered components in Figure 6, the USV produces three types of messages as discussed previously in Section IV.F: MC, S2, and GC messages. GC messages are for peer USV communications and are not addressed to the C2 module. The other two message types are directed and addressed to the CS module and are received by the external antennas of the unit housing the C2 module at (1). From there, messages are routed to the appropriate servers labeled (2, 3, or 4) for follow on action. In some cases the information is simply stored for later retrieval while at other times it is processed further as directed by the HCI Server (5).

Servers are divided into functional areas, and each server may have specialized applications that perform the duties assigned to them. Because this system uses standardized communications protocols, it is easy to add functionality later through the incorporation of additional servers and applications. The following sections will detail more specifically the duties of the Vehicle Information Server (2), the Sensor Stream Server (3), and the Data Server (4).

### 2. Vehicle Information Server (VIS) – (#2, Figure 6)

This server's primary responsibility is to store, combine, and forward all the MC messages. As illustrated in Figure 6, it has at least two databases, one for status updates, and one for position updates. Status updates are the messages that contain the regular "heartbeat" type information that conveys the health and operating modes of each USV. This information will be periodically supplied to the HCI module to refresh the state display of each USV controlled. Along with the status updates, MC messages will also contain updates on the positions of each USV. This information is stored in a separate database for easy retrieval to be supplied to the HCI module in order to refresh the displayed position of each unit.

The VIS also contains multiple applications to assist with recognizing and handling incoming messages. One of these applications, the Notification Handler, scans incoming MC messages for any notifications from the USV that the human controllers need to respond to. These messages will include advisories on equipment status, cautions when nearing operation limits, and warnings for when there has been a critical malfunction like fires or flooding.

To ensure proper information security, and repudiation, the VIS has a log file dedicated to recording the type and time of incoming messages before they get processed. In addition to this log file, every server will also have the required log files for proper forensic investigations should the system be attacked electronically.

### 3. Sensor Stream Server (S2S) – (#3, Figure 6)

The S2S server is primarily responsible for receiving the S2 messages from the USVs. Actions taken by the S2S will be directed by the human operators through the HCI module. The S2S will require significant data storage capabilities in order to store sensor streams for later replay or analysis. The Sensor Stream Handler application's purpose is to prepare a live stream for storage and works with the USV to ensure all stream data is received properly.

### 4. Data Server (DS) – (#4, Figure 6)

The DS, like the S2S, will also require significant data storage capabilities. The primary job of the DS is to store the commonly accessed, static data sets that are used by other applications on other servers. The most significant blocks of storage on this server include the intelligence libraries and the geographic information databases. The purpose of the intelligence libraries is to assist in the classification and identification of submerged contacts while the geographic information databases are used for route planning and USV positional awareness. The intelligence databases can either be resident on the DS or they could be remotely called from other servers aboard the host of the C2 module. These intelligence libraries should include, but are certainly not limited to Acoustics Intelligence (ACINT) and Signals Intelligence (SIGINT), which includes emitter libraries (ELINT). Linking up all these libraries may pose classification issues that will need to be addressed.

The DS also plays host to two related applications: a route planner, and a sensor analyzer. The route planner is invoked whenever the HCI module sends movement instructions to the USVs. The route planner consults the geographic databases and compares GIS standardized shapefiles to ensure the proposed route will not unintentionally violate any territorial boundaries or other geographic constraints imposed by operational intent, treaties, laws or other generally acceptable maritime regulations. If these conditions are satisfied, then movement commands will be generated and sent to the USVs, otherwise the application will fail-over to a human operator to handle the error condition.

The sensor analyzer application is likely the best candidate to employ an AI agent, as this application should take in live or recorded sensor streams from the S2S and compare them to the intelligence libraries to see if any of the sensor observations matches or comes close to matching known contacts of interest. This is also a place to conduct new intelligence gathering on unique observations.

## H. HUMAN/COMPUTER INTERFACE (HCI) MODULE

This section refers to items 5 through 8 in Figure 6.

### 1. The "Safe" Ratio

Conventional wisdom and research would both suggest that a 3:1 ratio of humans to robots is a safe-ratio for maximizing mission performance while ensuring the physical safety of civilians and bystanders [4]. However, this ratio obviously does not scale well. To be able to control many units, the representations of those units, and the lists of data associated with them needs to be abstracted to be easily consumable with a single glance by an operator. Ideally it only takes a new watch stander a few moments to get a "grasp" on the situation. Certainly there will be pieces of information that are not displayed, that an off-going watch stander retains internally, and this kind of information is best shared at a face to face watch turnover. This is only one part of the problem for which there is already a partial solution if you use the combat information center found onboard every warship as an example. Their situation awareness system pulls data from multiple sources and presents it on multiple displays throughout the information center. Shared pieces of data are updated simultaneously for all users to see. In this way, a single ship can control the combat efforts of many different platforms, while also acting as the hub of information.

### 2. Inspiration from Computer Gaming Industry

Using a game engine optimized for the display and tracking of a large number of entities is ideal for use in this environment. A genre of popular computerized gaming that comes to mind are the real-time strategy (RTS) games in which multiple players can control hundreds of units simultaneously. All the human and AI players in the game can simultaneously, in real-time, send their game pieces to do battle with all the other players. In some cases, there can be hundreds or thousands of units all fighting each other. Granted, these interactions come down to simple game formulas that take into consideration attributes that each unit possess like firepower, armor, maneuverability, speed. The score that each unit has in this category is combined with all the other scores to give a probability that a unit will be damaged in an engagement, or if its weapons will hit accurately.

The RTS-style of game is designed and optimized for tracking and updating the positions and actions of hundreds of units in real-time. Suppose this off-the-shelf technology is leveraged to be able to control many drone units. The idea may seem laughable at first, but consider the issue at hand. A single controller can monitor the actions, in detail, of one unit very closely, and can monitor the actions of several (about six) fairly well. However, the ability for the human to control in any meaningful way all six of these platforms diminishes as the task complexity increases. It is therefore necessary to abstract "housekeeping" tasks away and shift that burden onto something else. Let the human worry about tactics and strategy, and in trying to make sense of Disorder and Chaos, let the computer worry about whether the human's actions are possible or legal and how to actually execute them. The human should be the conductor to a symphony, not one of the musicians.

In this way, I think that an RTS game engine is superbly suited to help with this abstraction problem. Select a game engine that is affordable to license, has an easy application programming interface (API) to work with, and has great support for different operating systems and hardware configurations. Also, select one that has a good "feel" to it whose controls are already intuitive with a minimal amount of training required to become functionally proficient. Then, with that as a base, add in models for USVs along with any needed animations that are all closely coupled to the real world platform. The goal here is that if it takes thirty seconds for a unit to deploy its towed array in real life- it takes the same amount of time in the virtual world. This is mostly trivial for a seasoned team of game programmers to manage. The real challenge becomes this: keeping the virtual world synched up with the real world, and then how to handle situations that are not easily modeled—like a stuck rudder or failure to receive a movement order. These situations would need to be dealt with, even in an abstracted sense, so that the operator may still have a good sense for what is going on out in the operation area. Another challenge is in actually converting the commands given in the game world to real-world instructions to be acted upon by a live robot.

### 3. Display Considerations

There is a lingering question–if all the units have cameras, and radar, and an operator can effectively see "through the eyes" of the USV, why go through the trouble of creating a game world that is modeling the real world, in near real-time, when it would be easier for the operator to just "see" what there is to be seen? The answer is simply this: scale. The aforementioned display strategy works well for one vessel or a few…but beyond a certain point, it will become very demanding of communication resources. Considerable expansion of capabilities will be required to alleviate bottlenecks and constraints. These upgrades are expensive both in respect to time and money. Simply, this method will not work, and the game world offers many advantages.

Using a virtual representation of the battle space allows the user to view the battlespace from multiple angles. It also allows the overlay of helpful information, like predicted range of sensors displayed as rings or domes around a unit. Also, it can display geographic information and shapes as pulled from a common library and the shared tactical plot. A full 3D representation does not sacrifice the simplicity of a 2D top-down display; rather it can provide many advantages such as a moveable camera/point-of-view so that one may see the battlefield from multiple perspectives including the adversary's perspective. If the user wanted a more traditional view, then they could always flatten the perspective to see it more like a map.

Advances in wearable display technology can enhance SA further by more fully immersing the operator in the environment. This area is as yet unexplored and is ripe for further experimentation. Products like Oculus Rift and Microsoft Holo-Lens may offer the drone controller some unique display options. In Oculus, the user is not constrained to traditional monitor setups like dual or tri-displays and can experience full 360 degree field of view displays using software products like Virtual Desktop [27]. The tightest constraint is on graphics processor abilities and a designer's imagination. Experimenting with what the latency is like between the game engine and the vessel, as well as the game and the C2 sources, and the game and updates on adversary positions will be required to assess effectiveness of this option.

## I. ASSESSING VALUE

Broadly speaking, when people discuss the value of a product or service, they are usually discussing its cost in relation to a competitor's offerings, or perhaps other alternatives, to include making the object or performing the service themselves. This notion is therefore applicable to software and automated systems. There is one resource above all others that is nearly always insufficient in quantity and is non-renewable; this resource is, of course, time. This is not a groundbreaking revelation, but more a tautology of life that has such a strong gravitational pull that no idea can escape its force. Software and automation is often looked at to somehow save time, but in attempting to *hopefully* save some unknown quantity of future time, a finite and certain amount of current time must be expended in the process. Aside from time, money (dollars, Gold, and bitcoin) is another critically important resource in software development. While limited, money is thankfully renewable.

Time and money are presented here, not as a remedial economics lesson, but as a way of setting up a common language and giving variables names. From these two variables, other composite resources can be constructed, for example: Manpower could be considered as a function of time and money. Manpower can be viewed as the combination of the amount of time spent on training as well as the total cost of a person's training, salary, and benefits. Essentially, manpower is a two component vector, or tuple, that has a total training time, and a total cost. One could get more detailed and describe the nuances of retirement benefits and their monetary value or how all units of manpower should not be considered equal, as in the case of a plumber versus a fighter pilot, or how limits on force size and training capacity affect manpower, but for our purposes, we will concern ourselves with only the near-term costs. Other such composite values would be unit cost, which would be the total of the production costs and the maintenance costs, both paid for and pending, and failure cost, which is the total cost incurred if the unit was absent or failed to function.

The valuation of an object should also consider non-tangible values, like the amount of power or influence that can exerted. For example, a submarine wields some non-trivial amount of influence on local politics and international affairs in the region that it is operating in. A maritime state may leverage its physical submarine asset to generate power or influence, or to gain monetary concessions from another state. Unlike other forms of value, it is difficult to place a monetary or temporal value on Power/Influence, as they could evaporate quickly or have long reaching effects.

In a nutshell, the acquisitions officer or program executive office needs to consider tangible resources like time and money, and intangible resources like power and influence when trying to decide to purchase a certain USV or not. There are costs associated with the development, testing, fielding, and maintenance of a system that needs to be weighed against the cost or gain associated with using more people and then balance against the potential loss of power and influence with an adversary.

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# V. ADDITIONAL CONSIDERATIONS

The focus of this chapter is to discuss those considerations that are important and must be included into the design of a USV, and are best highlighted separate from the core of the USV design.

## A. SECURITY

This section address security concerns in more detail to highlight particular vulnerabilities that a USV might have and should be addressed early in the development process. Security in all of its forms is of the utmost importance to an autonomous system designed to operate outside the direct line-of-sight control of a human. Security needs to be “baked in” from the very beginning so that it works integrally with all the other systems. Too often in software procurement is security a “bolt-on” addition that gets added during later design spirals. While it is never too late to address security, it is unfair to say that some security is better than no security. Security that prevents the accomplishment of the mission is a waste, though security is frequently sacrificed in the name of mission accomplishment with the flawed hope of “security through obscurity.” This is an untenable position, and it is better to assume that systems are always being attacked than the alternative.

### 1. Cyber / Electronic

It would not be an exaggeration to state that hundreds of books have been written on the topic of computer security, particularly cyber-physical and information security. Broadly speaking, computer security covers a very wide range of topics that each has quite a bit of depth to them and includes topics such as: network, storage, and application security. This thesis cannot hope to do these topics justice, but aims to increase the reader’s sensitivity towards critical cyber vulnerabilities.

In the current generation of cyber-physical platforms, the major goal has been to field a platform that provides value added to the warfighter. While going forward, this will continue to be the case; but the old paradigm of “just get it working” will not stand.

What our adversaries may lack in firepower or lethality, they make up for in cyber-warfare skills. No system is safe, and even without a network connection a system is still vulnerable; add in a network connection, or some sort of external communication link, and the problem space expands. It is worth remembering that security and access are diametrically opposed; one may have all of one and none of the other or else a compromise must be met.

When discussing cyber security the concept of an "attack surface" comes up. To visualize, imagine a three dimensional cube with six faces. As any dimension of the cube is modified, the surface area will similarly grow or shrink depending on the change. In the cyber world, a computer system could have multiple software layers or "faces," with each one with its own surface area. Changes to one surface may cause a change in another depending on how tightly coupled they are. As a system increases its external connections, applications, and even lines of code in a program, it exposes that system to greater risks through known and unknown vulnerabilities—otherwise known as growing the attack surface. The target that a hacker has to hit has become larger, and the job for the defender has become tougher because of the increased area to be defended. When designing a cyber-physical system like a USV and its supporting infrastructure, careful attention needs to be applied to how big the attack surface is becoming. At some point, the surface area will become indefensible, and there will be multiple leaks that a defender has no chance of combating. When this occurs, it is important to have a robust information security plan.

In classic military planning, the entrenched defender is assumed to have a nearly three-to-one advantage over an attacker. This defensive multiplier is granted due to the defender's knowledge of the local terrain and with the defensive perimeter. Also, the defender does not need to exert the same amount of effort as an attacker must to overcome the entrenched positions. This model does not apply to cyber, as the attacker only needs to find a single "chink" in the armor of the defender and they may then be able to gain full access to the defender's system. For safety systems in aircraft, like ejection seats, the minimum acceptable failure rate is zero—the system needs to work correctly the first time, every time, or else it is defective and is replaced. This is essentially the problem facing the defender, which needs to stop the attacker at the first sign of aggression, every time. When the attack surface increases, this becomes less and less attainable.

The recommendation to the designer and stakeholders is this: install the hardware and software needed to complete the mission and nothing more. Then, with that initial configuration, trim all remaining "fat" from the software by removing unneeded functionality. Rest assured, if a certain function is required at a later date, it can be installed, but there is no need to have it until then. Consider this simple example: unless one is an avid fan of a gaming application that may have come preinstalled on their system, such as Microsoft's Solitaire, then consideration should be given to removing the application if reducing the attack surface of their home system is desired. This is a simple example to illustrate the point, but consider such programs like Skype and Google Maps that require access to onboard cameras and location data to "function properly." These types of exceptions open a user up to an actor that seeks to install malicious software that may pose as one of these legitimate applications. Because the permission has already been granted, the operating system may not detect the deception and could allow the malicious program to run with access to video and locational data, which should be private.

### 2. Information / Data

As the saying goes "knowledge is power;" applied to today's world, knowledge is derived from information and roughly equates to information access. To be clear, consider the term "knowledge" to refer to an individual's interpretation of the world around them influenced by their experiences, biology, and personality. A helpful explanation is found on [28] that states that "data is/are the facts of the world" or a "description of the world." Data is therefore constantly present but not always recorded or observed. According to [28] information is then data captured. The three terms, knowledge, information, and data, are often used interchangeably and therefore, it is important to make the distinction going forward.

The concept of data states is widely known in information security; it is worth reviewing here with some common examples:

- Data-at-rest: information which is stored on some form of storage media, to include: hard-disk drives, optical disks (CD, DVD), and removable drives like USB thumb drives. To be more precise, it is information that is stored in non-volatile memory.
- Data-in-transit: information that is being transmitted from non-volatile memory into volatile memory like random access memory (RAM), or is being transmitted across a network connection.
- Data-in-use: information that is stored in volatile memory, and is being used by an application, thread, or process.

These data states are illustrated in Figure 7.

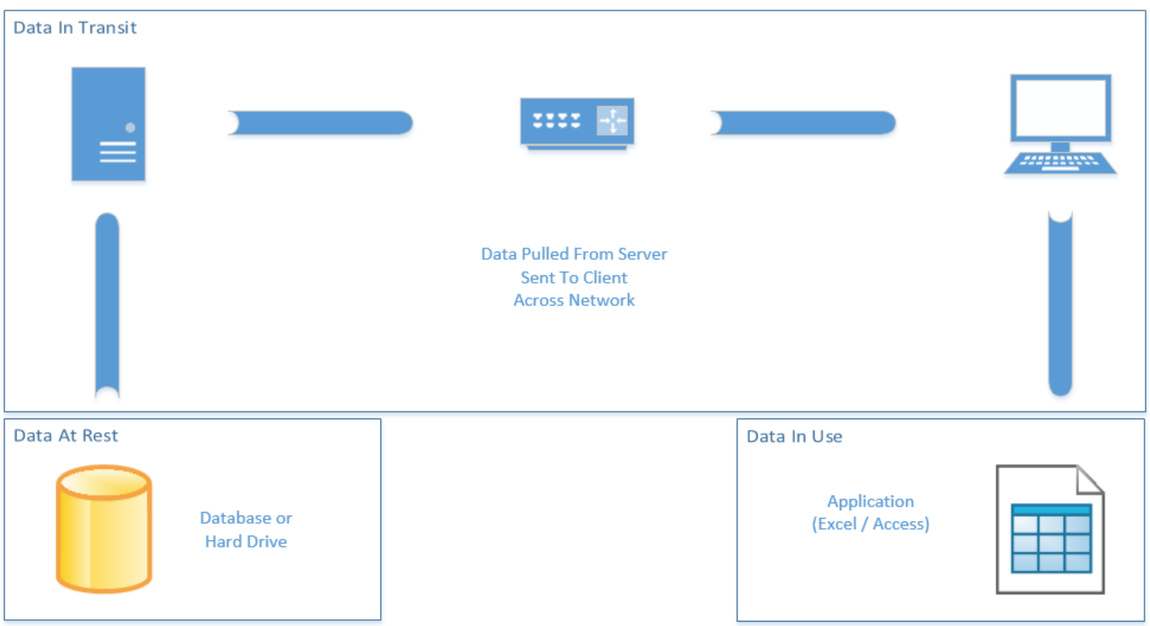


Figure 7. Data States

Information security is concerned with protecting information at each one of these states. The success of security measures depends on the state, as each one has unique challenges and vulnerabilities. The most difficult state to protect is data-in-use because it usually resides in RAM and is typically un-encrypted. It is functionally impossible to use encrypted data because at some point, it must be de-encrypted to be able to view or modify. This information is usually the initial target of attackers as it is "on the surface" and with the right tools can be easily accessed. However, this often requires physical access to the machine with the information, as once it leaves the application or RAM, it will be encrypted.

Data-in-transit is vulnerable to interception, by any number of man-in-the-middle type attacks or spoofing. If one wants to ensure the security of the information, then it must be encrypted, otherwise it is as good as if the hacker was invited onto the network. However, encryption is not free and comes at price. First, many encryption algorithms use a technique called padding to ensure chunks of data are of the same size. Second, it takes a finite amount of time to run the encryption/de-encryption algorithm so that there is time before transmission to "package" the message, and then time on the receiver end to "unpack" the message from the encryption. The time intervals required for this process are small (microseconds), though these fractions of seconds compound quickly for a large messages.

Data-at-rest is the most common state the average computer user thinks of when discussing information security concerns. The reasoning is simple – everyone knows that information is stored on or in something, though this understanding may recede with the growing prevalence of the "cloud." As an aside – "the cloud" is no different than storing files on a shared-drive, just the implementation is slightly different and the mechanisms are more obscured. Given this understanding, it is fairly intuitive to understand the desire to protect data while it "just sits there." Much like a file cabinet in an office that contains sensitive files; one does not want just anybody coming in and browsing through the files. Encryption for data-at-rest does not add any more overhead from encrypting data-in-transit, if the files are stored directly. Otherwise, there will be a slight delay before writing so that the files may be encrypted and one can expect that files sizes will be slightly larger than the same file in plaintext. The primary vulnerabilities for data-at-rest are theft and destruction. Files written to storage media can be copied to another volume and then an attacker can attempt to crack them at leisure. Because these files are non-volatile, and are not being transmitted, the temporal aspect in capturing this type of information is diminished.

How far into a system an adversary can get will determine how much information they are able to view and subsequently steal. This is a real risk for an autonomous vehicle because by design, it needs external communication ports and will likely be storing some amount of data onboard for further analysis or processing. While the risk of interception is ever present, it can be mitigated through encryption, with the understanding that it comes at a cost. Additionally, measures can be taken to secure the information that resides on the platform. However, the best way to prevent the adversary from gaining information is for it not to be there. The designer in conjunction with the stakeholders needs to consider carefully what information is gathered and stored aboard the vessel. Given sufficient time and resources, a determined adversary will be able to crack most security and encryption protocols, so the goal is to delay them as long as possible to ensure that whatever information they do recover is sufficiently old as to not provide a tactical or strategic advantage, to include gathering information on the collection mechanisms or processes.

In short, the following is recommended: Autonomous vehicles, especially those at risk for isolation and therefore capture, should follow computer security industry good practices to prevent the interception and modification of information during any state of use. Failing that, it is imperative that robust checks are performed on mission critical information to ensure authenticity and non-repudiation.

### 3. Communications (COMSEC)

This USV will not need to use voice circuits, but it will need to transmit/receive information on data circuits. The goal of this USV design is to keep all the classified sources of data aboard the mother ship/base station and not on the individual USVs; this allows them to be more expendable and alleviates some of the concerns surrounding an adversarial capture of one of these units. However, even if the data itself is unclassified, there is no need for an adversary to be able to see it plainly. Therefore, most data going to and from the USV should be encrypted compatible with the designated classification level required for the type of data being transmitted.

Special consideration is required in the design process to ensure that the USV's communication systems will be compliant with standing COMSEC policy. Additionally, it will be necessary to consider how to implement the ability to "zero-ize"/erase onboard communications gear to ensure the encryption keys do not become compromised by an adversary. This level of encryption protects data while in transit, but it does come at the price of increased amounts of data needing to be transmitted. Most encryption algorithms carry a small data overhead depending on how they divide data into chunks. While this overhead is generally small for Internet applications, it may be more restrictive for vessels that have limited bandwidth and connectivity.

#### 4. Operational

Operational security (OPSEC) is a set of security concerns that can impact the successful completion of a mission. The most well-known phrase in the OPSEC community is, "Lose Lips Sink Ships," coined during WW2 to remind service members and citizens to be mindful of their discussions about sensitive information. This notion carries over to the electromagnetic spectrum as one can never be too sure of who is listening to their electronic conversations. This is germane because the USVs in this system are not fully autonomous and will require periodic communications back to a controlling station.

A radio frequency broadcast signal in the UHF/VHF band is often transmitted Omni-directionally and therefore is subject to intercept by any receiver in the line-of-sight of the radio wave. It is possible to use beamforming techniques to make a transmission more directional, though it then becomes important that the intended receiver is oriented correctly to pick up the transmission. This is often difficult to achieve with moving platforms as it requires both platforms to be synchronized with each other, a problem whose difficulty increases greatly with an increase in degrees of freedom of movement. RF data transmission is useful for LOS operations, but is often more costly and challenging for over-the-horizon (OTH) transmissions. Even if the content of the transmissions is encrypted, that fact that a station is transmitting provides valuable intelligence to an adversary. For example, if an adversary is monitoring a region and notices an absence of visible maritime traffic, but it sees a spike in RF transmissions from this same region, then a reasonable conclusion is that there is something there that is either camouflaged or is too small to be ordinarily detected.

To alleviate the concerns with LOS communication one may choose to use a lower frequency signal that can bounce through the atmosphere or a highly directional transmitter may be chosen. Often, this transmitter comes in the form of a satellite antenna that is oriented to a satellite in orbit. While offering more security, it is not without its drawbacks including limited quantities of communication slots available for assignment. Just because a unit wants to use a satellite, does not mean the resources will be made available to them for their use. Another alternative to RF transmissions is an acoustic modem though they are still subject to counter detection by a submerged listening platform.

### 5. Physical

The physical security and safety of the USV system is important to the safe and effective employment of this system. With the exception of ACTUV/*Sea Hunter*, most USVs are quite small in comparison to warships. This small size makes then vulnerable to harassment, tampering, theft, and destruction by virtually every manned platform. While this issue could be dismissed as an engineering or policy issue, it is fundamentally a software issue as well. Upon detection of some sort of disruption event, the USV needs to take immediate action to ensure the security of its onboard data, encryption keys, and overall safe operation to include the notification of the C2 module that the USV is being assaulted.

#### *a. Anti-Theft / Anti-Tamper*

The relatively small size of most USVs makes them vulnerable to threats that would not concern most other warships. Specifically, because of their size, they are more likely to be stolen by those seeking to sell the platform on a black-market, pilfer parts, or vandalize it for the sake of amusement [29]. Additionally, these platforms would be more at risk for detainment and possible physical intrusion attempts by an adversary.

Therefore, it is necessary for the USV to detect when it is being interfered with and take appropriate actions.

A possible scenario is that an adversary vessel comes upon one of the USVs and then decides to bring it aboard in an attempt to sabotage the USV. The easiest way to detect this kind of tampering would be to have a temperature probe on the bottom of the USV that if it should be exposed to free air would register it has been removed from water. In case the USV got flipped over by wave action, then onboard acceleration sensors should have detected the roll movement and reset the Out-of-water timer.

In the same scenario, if the adversary attempts to open the outer shell of the USV without proper authorization, then it should register this and immediately delete all log files, encryption keys, and send a transmission to the C2 module that it has been captured. These scenarios highlight a need to have a robust physical intrusion detection system that will preemptively clear all stored data, the assumption is that it is better to have to recreate data from a backup then to allow data to fall into an adversary's possession.

#### *b. Legal Issues*

Rhetorical question: Is a USV considered a sovereign military vessel, subject to all the rights and privileges bestowed upon active commissioned warships, or is it simply a piece of property, like a wrench or a rifle? Does this change when a nation commissions a USV into its roster? A partial answer to this question is found in [30], which are the remarks by Deputy Secretary of Defense Bob Work. In his remarks, he suggests that the Navy should consider vehicles like the *Sea Hunter* to be "warships" not "drones." One can quibble over the semantics, but the idea here is that a warship is a "warship" whether it has a crew or not. If this is the case, then one can speculate that the laws that apply to crewed warships should also apply to non-crewed warships.

This leads to a troubling thought. If an unmanned vehicle is considered a "warship," then will the United States go to war or retaliate against another state should they sink or otherwise damage the vessel? The author posed this question in an email to the notable CAPT Wayne Hughes, author of *Fleet Tactics and Costal Combat*, who was quick to point out that asking what a response would be is the wrong question. Instead he suggested the following:

> Instead of saying, "what would be our likely response" the first question is "what are our choices?" Not the choices listed [interpret attack on the USV as an attack on a sovereign warship, treat attack like vandalism, or ignore the attack] which are wannabes. First comes what we can do, second comes what we should do. [31]

The resolution to this question is important for designers, because it will influence aspects of the design, particularly evasion and self-defense. If the vessel is a considered a "warship," then it needs to take all reasonable actions to avoid capture and to defend its self. However, where does one draw the line on defense, how hard should the USV fight for its survival or freedom? These are questions better left to other professions to answer.

## B. MANPOWER

Manpower represents one of the largest variable costs associated with implementing this software and probably one of the hardest to accurately predict. The software, once developed, has a negligible reproduction cost, though a non-trivial one-time setup cost will apply. Code maintenance will also be another variable cost, though if managed properly will be predictable. To make this software effective, it needs to be able to save the customer money that it would use on other assets. It is my belief that this system could save thousands of dollars that are normally spent on expending non-reusable sonobuoys or operating maritime air assets. Ideally, this system would also allow you to save on the amount of people being used to operate and maintain the system or enable better ASW coverage with the same number of people. This becomes a sticking point.

In *Human-Robot Interactions in Future Military Operations,* there are two essays, [4] and [32], that touch at the heart of this matter that almost appear to be both complimentary and contradictory. In the first essay, titled *The Safe Human-Robot Ratio*, the authors propose a ratio they believe provides the minimum number of people to operate an unmanned system and still be safe. This ratio is defined as $N_h = N_v + N_p + 1$, or plainly: The number of humans ($N_h$) required to safely control an unmanned system is equal to the number of vehicles ($N_v$) plus the number of payloads ($N_p$) plus one [5]. The authors use a lone, single-payload UAV as their base example. This platform, by their ratio would require three humans to safely operate. During their research they saw that most unmanned systems break down human tasks into three major roles: pilot, mission specialist, and flight director/safety observer. The pilot's goal was primarily to ensure that the aircraft did not collide with any objects and to be in a position that allowed the Specialist to use their sensor to observe the mission area. The director was responsible for keeping overall situational awareness of the larger mission, and to integrate what the specialist was seeing and what the pilot was seeing.

To apply the above equation to this project requires a little more refinement. Specifically, the constitution of a payload is left undefined, and so for our purposes let us define it. Conservatively, a payload could be each of the major sensor packages, so that would be sonar, radar, FLIR. Less conservatively, one could separate the sensors into broad areas of Acoustic, and Non-Acoustic, and then assume that the operator would not be focusing on FLIR at the same time as radar, and therefore one could safely combine those activities. At this point, the total number of payloads is between two and three. Now, applied to a squadron of say 16 USVs, that would be sixteen (16) USVs plus thirty-two (32) payloads (2 x 16) plus one (1), results in a manpower requirement of forty-nine (49). That is unacceptable, as that is about one-sixth the crew complement of a destroyer. Clearly the equation does not scale well if one is considering employing multiple USVs.

In attempt to minimize this number a developer may suggest that automation is the answer—that it is necessary to "increase the level of automation" to be able to perform more tasks that would have been done by a human. This is fair reasoning, but it can be problematic. First, one needs to understand how further automation is achieved, and likely, in the case of robots and USVs, the answer comes in the form of Artificial Intelligence. However, AI is not the panacea that one might make it out to be, as previously asserted in earlier chapters, AI is nothing more than fancy software. At the base level it is operating on a set of rules that human developers defined, or through other software, allowed the AI agent to define. It should be obvious that this path inherently leads to errors, some of which may be quite insidious and not manifest under normal test and evaluation conditions.

The essay presented in [32], *Lessons Learned from Human-Robot Interactions on the Ground and in the Air,* discusses how automation is not the answer for reducing the amount of people in the loop. The salient point in this discussion is that it is flawed reasoning to believe that removing the human from "the loop" will result in a decrease in errors. Certainly errors related to human carelessness or incompetence may be avoided, only to be replaced by a different set of problems. This problem set occurs when humans have been removed from the decision making loop and are cast into a supervisory role but are then required to intervene and take control of the USV during certain error states, like an emergency. When this occurs, the human's like of tacit situational awareness means that the human is reacting far slower than they would have been if they had been in control all along.

This argument complements another argument from the first essay of the same document in which the authors of the safety ratio propose that seeing the problem of automation as being similar to an Air-Traffic Control (ATC) scenario is fallacious. The reasoning is that while an ATC may have many aircraft under their control, there is a pilot-in-command of each aircraft who is in charge of dealing with local abnormal conditions, to include emergency procedures. It is not as if the ATC will suddenly take remote control of one of the aircraft and handle nuanced execution of procedures.

I present these points of view for the audience's consideration, as they fundamentally impact how many humans must be employed to operate multiple USVs. My argument is mostly technical in nature, that it is possible to present information necessary to execute the control of USV from a limited number of human interface points. However, the determination as to whether or not that is a good idea will require prototyping and testing to assess safety and performance under abnormal conditions.

## C. TRUST

Trust is a rather broad issue when discussing automated systems, and is a current philosophical question that the robotics community is wrestling with. Trust comes in many forms: explicit trust is usually defined formally through a contract, which may be physical or verbal, and the responsibilities are clearly delineated. Implicit trust derives from explicit trust, in the way that we trust doctors or pilots. We are not party to their actual qualifications, but we have implied and imparted trust to them based on their station. In all situations trust is usually earned through the demonstration of some set of actions that establishes confidence, but it can be quickly voided when decisions are made that are counter to the understood norms. For instance, the trust in an airline pilot is irrevocably lost if the pilot shows up to work drunk. Loss of confidence in professionals is not solely confined to workplace incidents. The errors in judgment that professionals make while away from the office also can cause a loss of trust. Professionals are expected to behave a certain way both on and off duty, and when these expectations are not met, their professional judgment abilities are called into question. Once this erosion begins, it is hard to recover.

How then is this applicable to autonomous systems and robotics? First, through test and evaluation and eventually acceptance testing, we establish confidence that software will work correctly most of time, and that it will accurately report when it is not working correctly. However, to ask a rhetorical question: what happens if the software does not recognize when it is wrong, or fails to report the situation? Can you continue to trust the software? Do you fire it, or revoke its license? Obviously it is hard to hold software accountable, so the axe usually falls on a programmer or some other poor soul involved in the development. Yet, in a system that is designed to go over the horizon and to meet the enemy, we are placing a great deal of trust in the system in that it is reporting back correctly. Also, we are putting a lot of faith in the programming that it can recognize a fault, or when it is tampered with. However, this thought is not justified, as it is nearly impossible for a machine to recognize that it has changed, and it is functionally impossible to test every possible state a piece of complex software could be in.

## D. MAINTENANCE AND UPKEEP

Designing with upkeep and maintenance, to include upgrades, in mind is part of a fundamental course in programming. Most instructors who teach programming classes will insist that their students diligently make comments about their code, and that even without the comments, names of modules, functions, and variables should all be easily understood. The idea is to have the code “talk” to another programmer without needing the original designer present to represent their code. The concepts of object oriented programming, along with modularity, are fundamental learning points in programming. In fact, as projects increase in size and complexity, it becomes imperative that the design team ensures that their work remains modular. The driver behind these ideas is in a word: change. Requirements frequently change, APIs change, and even the nature of the problem may change. Therefore, it is important to begin the design process with this idea in mind—while the design team may be the creators; they certainly will not be the last hands on the project.

When assessing the total cost of ownership of an unmanned system, the consideration for software upkeep must be addressed. This aspect of software is often the part of the iceberg that sits below the water, as it can cost a company half of the procurement costs in maintenance over the life cycle of the software. Intel in [33], estimates that over the course of supporting a software product, a 70% to 85% of the TCO will be absorbed as support costs. Support includes patching, training, and upgrades to the software system.

## E. ARGUMENTS AGAINST AUTOMATION

There is an idiom that is apropos to automation-just because something can be done, does not mean it should be done. There are multiple instances where automation could assist the work that a human is doing, or could replace the human entirely. However, there is a price paid in removing the human from the equation.

Humans are inherently lazy, it is not that we mean or desire to be slothful; it is just that we have a tendency or predilection for procrastination and complacency. By allowing a computer to perform certain tasks in a combat environment, a sailor may become complacent with the output of the machine and fail to be on guard for errors. For example, in the case of automated target tracking, when inexperienced crew members rely too heavily on the computer, their practiced skills atrophy and they become distracted by other tasks. This distraction can mean the difference between detecting a submarine, and allowing the submarine to pass undetected to sink the HVU.

As we allow machines to perform more and more tasks for us, we cede control over events and risk becoming passengers to our AI drivers. In combat, mistakes can be fatal, and overly relying upon machines and software could be deadly. The victor of the next major conflict will be the one who did not overly restrict their machines, but also did not allow their human assets to become too reliant on those machines. Humans require food, water, and shelter to survive; creative outlets and purpose to thrive [34]. An autonomous system requires information for both. Restrict the information flow and you starve the automaton.

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# VI. FUTURE WORKS AND RECOMMENDATIONS

During the course of my research, I discovered many topics that could be interesting for follow on research. It is with regret that I did not have time to pursue every avenue and so I leave these bread crumbs for fellow scholars.

## A. FUTURE WORK

### 1. Operating in Fully Degraded Communications Environments

One of the primary assumptions made during this design was that the proposed USV system would be operating in a communications environment that was either fully-permissive up to partially-degraded. The over-arching assumption being that the U.S. would have the same control over the EM spectrum that we have had in previous confrontations. Unfortunately, this is an unsafe assumption to make when considering peer or near-peer adversaries. The People's Republic of China is the country to most recently demonstrate an (anti-satellite) ASAT capability and planners should consider that they might freely export that technology to other countries. With ASAT capability, one cannot assume that they will be able to use GPS and other satellite based communications during a confrontation with these states. This has major implications for a USV that relies on GPS, as they could become an effective mission-casualty at the opening of hostilities. Further research is necessary to determine backup systems that can be installed which do not overly encumber the platform. One recommendation is to use an inertial navigation system, but a limitation with these systems is that they periodically need to calibrate off a fixed position. Radar could be used to establish radar lines of bearing if in close proximity to the coastline, and other OTH transmissions like LORAN have been used in the past to help triangulation efforts. A significant vulnerability for this platform, and the U.S. military as whole, is the over-reliance on GPS. Manned platforms would be superior in this regard as they can fall back to paper charts if necessary, though this too is becoming increasingly rare skill. Alternatives are necessary if the goal is to use these systems the day after the GPS has been disrupted.

### 2. Sense Making for ASW

While exploring the material and the theory behind the Cynefin model, and learning about organizational and operational complexity it occurred to the author that applying the Cynefin model and other products from Creative-Edge may yield some valuable insights into ASW. ASW is a domain that has atrophied and is slowly resurging in Navy circles; however it would be beneficial to the organization to capture some of the cognitive processes that go into fighting submarines that could improve the warfare area in general, and enable smarter use of autonomous systems in particular.

### 3. Classification Issues

My proposed model includes pulling from the ACINT and SIGINT databases, however to combine these abilities onto one system may make the system too classified for operational use. The ideal mission system will have a classification of no higher than SECRET. The basis for this recommendation is that higher classification level will make the USV control system inaccessible to a large segment of the shipboard workforce. Ultimately the USV module, the C2 module, and the HCI module do not require knowledge on collection methods and sources, just the signatures. Coordination with specialists in this field should help the designer avoid difficulty in this area.

### 4. User Interface Prototyping and Use Study

I made the claim that the Human Computer Interface or User Interface portion of this system was one of the most critical components. The C2 module is certainly the brains of the operation, but to the warfighter—it is and should be transparent. This makes the HCI module the heart of the design. The only way for an operator to truly be able to control multiple assets, is to have good situational awareness of where all their assets are. This is impossible to accomplish with a muddled, non-intuitive, non-user friendly interface. If the button-pusher has to think more about what sequence of commands are that need to be issued versus just commanding, then the whole enterprise is lost and will quickly sap value.

To this end, it is necessary to conduct a task analysis and rapid prototyping of some UI mockups to start getting instant feedback from the end user. The closer the controls can mimic triple-A video game design, the more intuitive the controls will be to a user, and the payoffs will be noticeable: quicker time to train, minimized error rate, higher situational awareness. However, the study must be commissioned and performed to start capturing those data points.

### 5. Valuation Functions

Chapter IV, Section I, discussed assessing the value added by an autonomous system. The author initially began work on developing an equation / process to try to assign a measure of value to dissimilar UMS. One of the chief difficulties of this approach was how to judge the value, other than monetary, of two different UMS performing the same mission, but in different domains. For example, how does one compare a USV for ASW against a UAV for ASW? The stakeholder wants to know what system they should invest in, and presumably they have an idea as to which domain they would prefer. Considering their needs, it could boil down to "it depends." Consider a more likely scenario: two USVs that are designed to perform the same mission, developed by two different manufacturers and are roughly the same cost…which does one choose, which is better? The answer would initially be "it depends" but one could establish a set of benchmarks for the systems to tackle, and then depending on the result, choose the best. Short of a decisive victor, it comes down to a qualitative or "gut" decision. Ultimately, the idea was scrapped because it gets intractable quick, with not a lot of "value added." A consumer considering a car purchase is likely to buy from the manufacturer that they have established a familiarity with over one they have not; the exception being: a less familiar alternative is so greatly superior in quality or price as it would be illogical to choose otherwise. The conclusion was that in the case of a clear victor, no equation would help, and in the case where it is inconclusive, then a quasi-scientific numerical approach would not sway the gut of a stakeholder.

### 6. USV Group Leadership

In human organizations with hierarchal structures a leader usually does not have direct communication with more than three to six individuals. While a single leader may be responsible for hundreds or thousands of people, that leader usually does not have meaningful direct contact any more than the three to six. As previously discussed, this is likely due to limits on human capabilities for multi-tasking. This type of organization scales pretty well as demonstrated by military organizations. The question becomes, does an organization like this help when dealing with multiple USVs.

The benefits to selecting a single USV to be the leader of multiple USVs, like in a formation, are many. First, selecting a single unit to be a leader allows the human operator to abstract away the rest of the units and then deal with a grouping collectively by issuing instructions to a single unit. That unit then has the burden of parceling up instructions—a problematic situation. However, if the leader acted as a relay, it could communicate with units that were a further distance from the main communications node and act as a place for those units to store and forward messages back to the main entity.

Other issues also arise such as how do you initially select a lead? Does the lead remain static? What happens if the leader can no longer remain with the group or is destroyed?

## B. CLOSING

Unmanned systems of all shapes and sizes are the new normal of modern warfare. As a country, we can ill afford to lose the advantages we have in unmanned and autonomous systems, and we must strive to close the gaps between us and our competitors. Through this work, it has been the motivation to help support those who develop the next generation of unmanned vehicles for the war-fighter. It is the author's hope that other scholars will pick up where he left of, and continue to tease out ways of achieving the ultimate goal of many unmanned vehicles under the control of a single human.

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